The ATLAS experiment upgrade and expected physics performances at the High Luminosity LHC

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Motivation for High Luminosity-LHC

Many physics achievements by LHC & experiments

- Higgs boson found (2012++)
- Several rare decays discovered (e.g. $B_s^0 \rightarrow \mu^+\mu^-$, …)
- CP violation in B sector (e.g. $B_s^0 \rightarrow J/\psi\ \phi$)
- Standard Model is describing measurements well

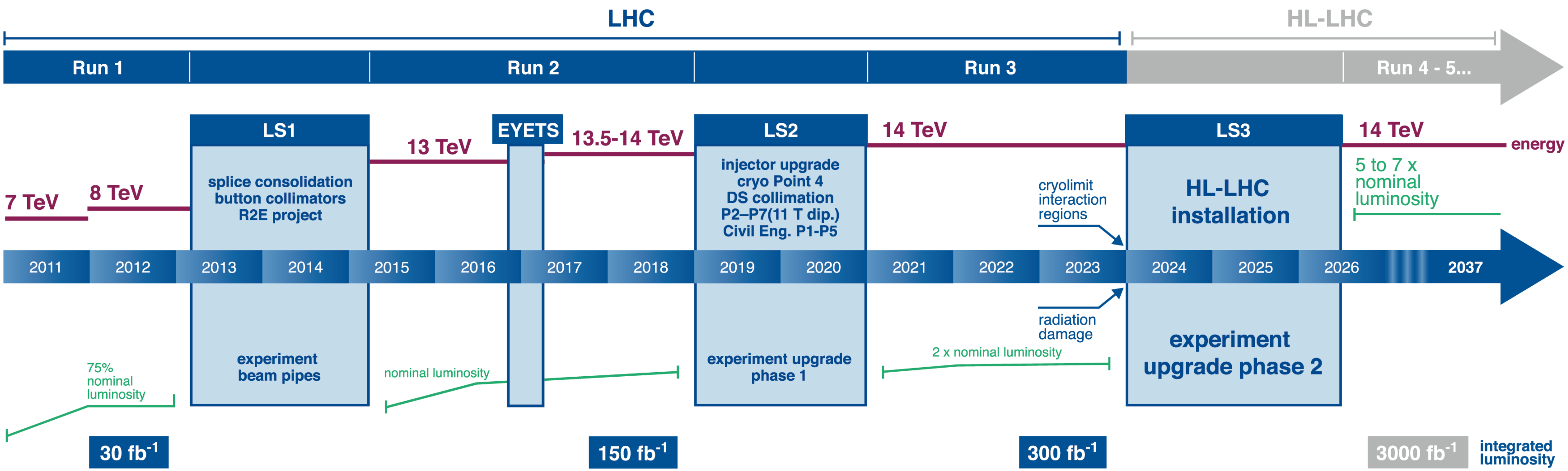
Many puzzles remaining

- Dark matter → New type(s) of particles?
- Supersymmetry: Does it exist?
- Flavor anomalies: LFV, LFU violation?
- Matter-antimatter asymmetry
  → How to explain it? CP violation only?

LHC at or above design performance

- Already at $L_{peak} = 2.06 \times 10^{34}\ cm^{-2}s^{-1}$ (2 x design)
- E_{CMS} = 14 TeV expected for Run 3
- ➔ Expect only linear increase in $\int L\, dt$ after Run 3
- Need more to improve measurements
- ➔ Upgrade LHC and experiments to High-Luminosity (HL) phase

LHC / HL-LHC Plan



Run 1

Magnet splice update

Run 2 at ~full design energy

Phase I upgrades (injectors)

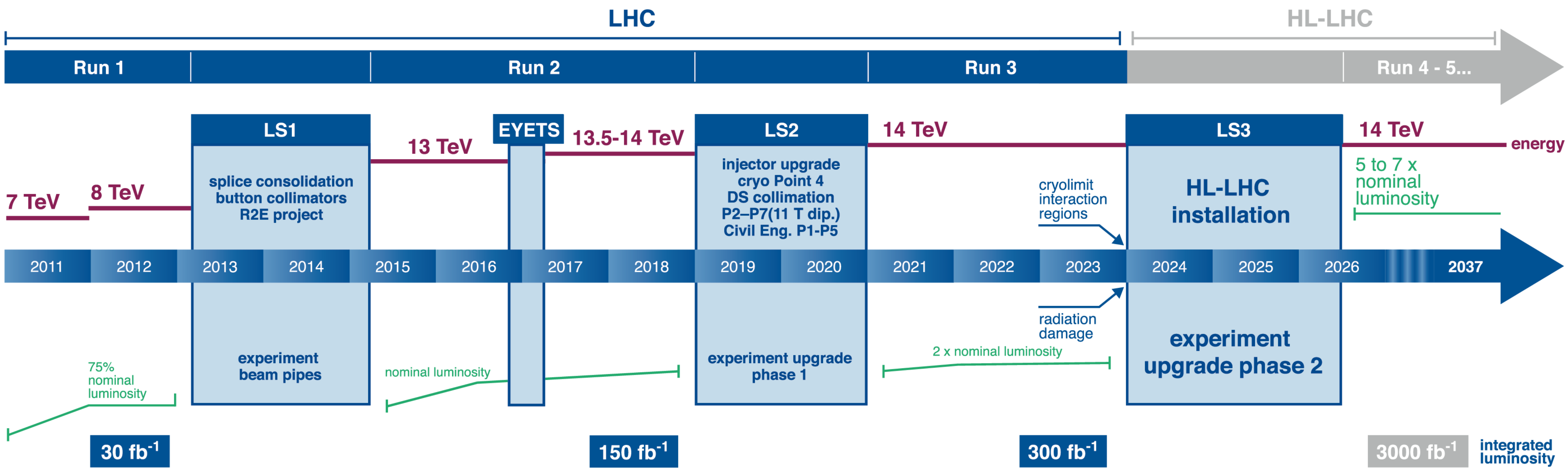
Run 3 at original design lumi

Phase II upgrades (final focus)

HL-LHC: ten times design lumi

HL-LHC mode	Peak Luminosity ($cm^{-2}\ s^{-1}$)	Mean number of interactions per bunch-crossing $<\mu_{PU}>$	Integrated luminosity (fb^{-1})
Baseline	$5x10^{34}$	**140**	**3000**
Ultimate	$7.5x10^{34}$	**200**	4000

LHC / HL-LHC Plan



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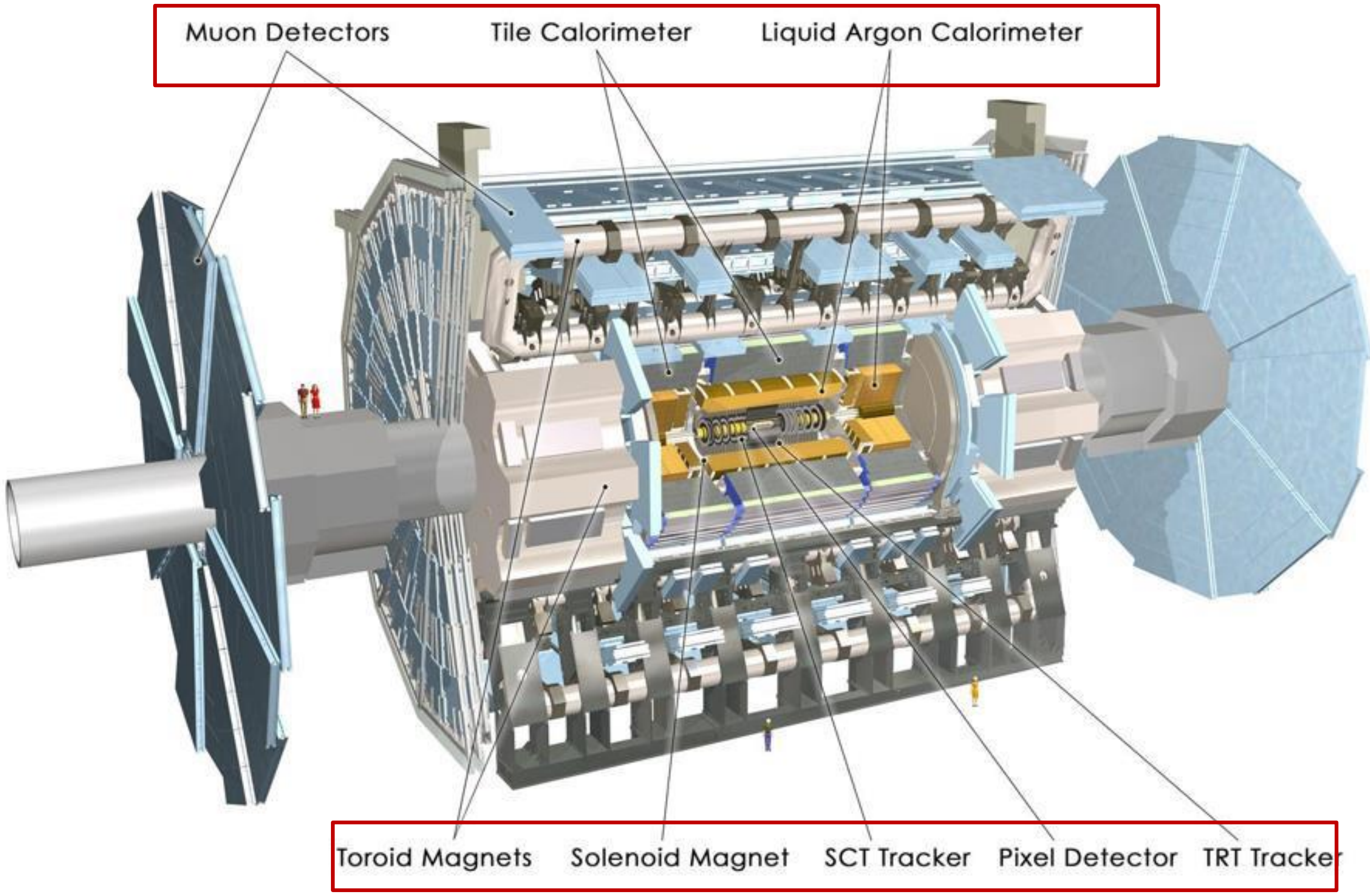
Full exploitation of LHC is top priority in Europe & US for high energy physics

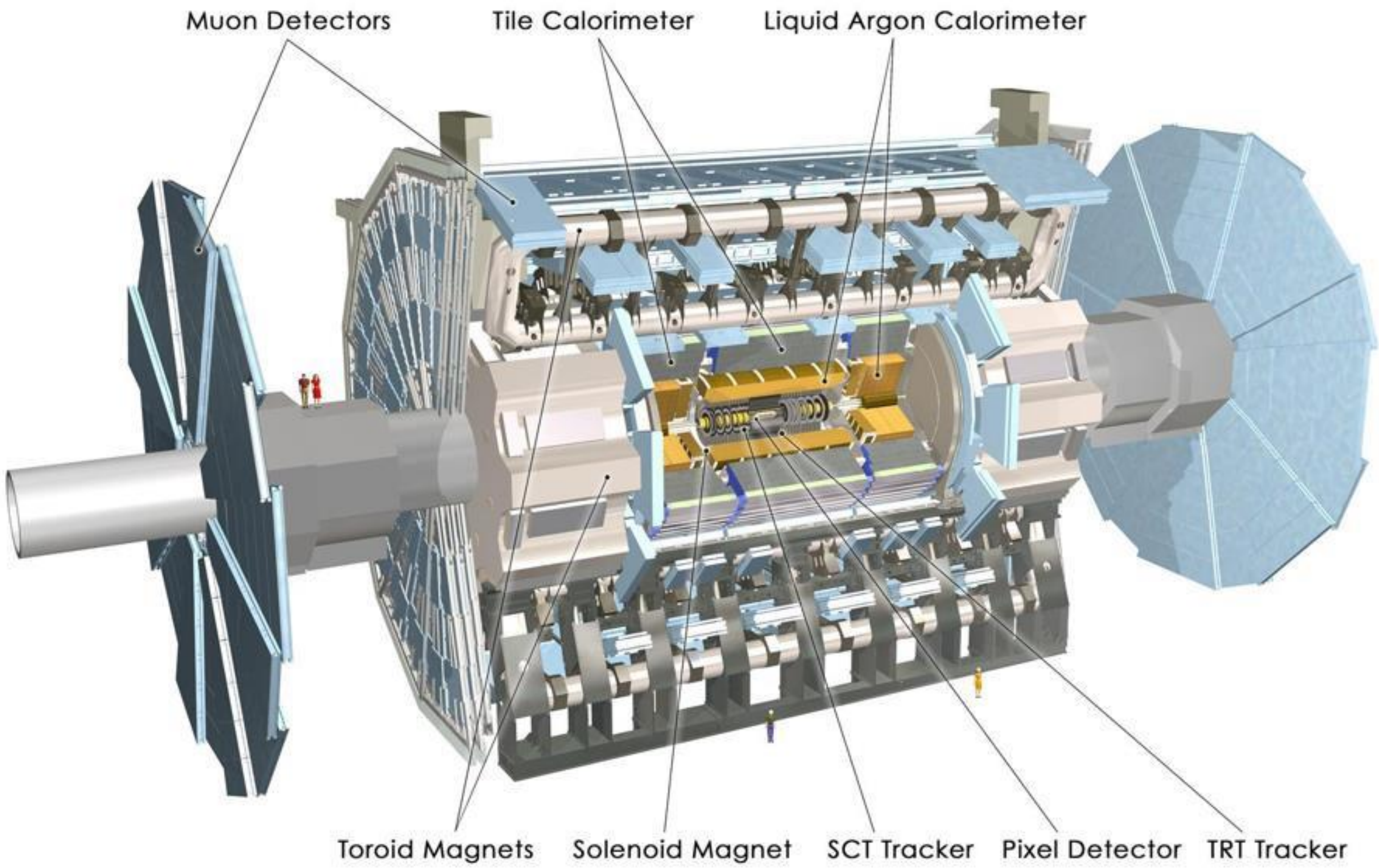
Operate HL-LHC with 5 (nominal) to 7.5 (ultimate) x$10^{34}cm^{-2}s^{-1}$ to collect 3000/fb in order ten years.

The ATLAS detector upgrade program



The ATLAS detector upgrade program

TDAQ upgrade
➔Increased latencies and rates :
--L0[6µs. 1MHz]
--L1[30µs,400kHz]



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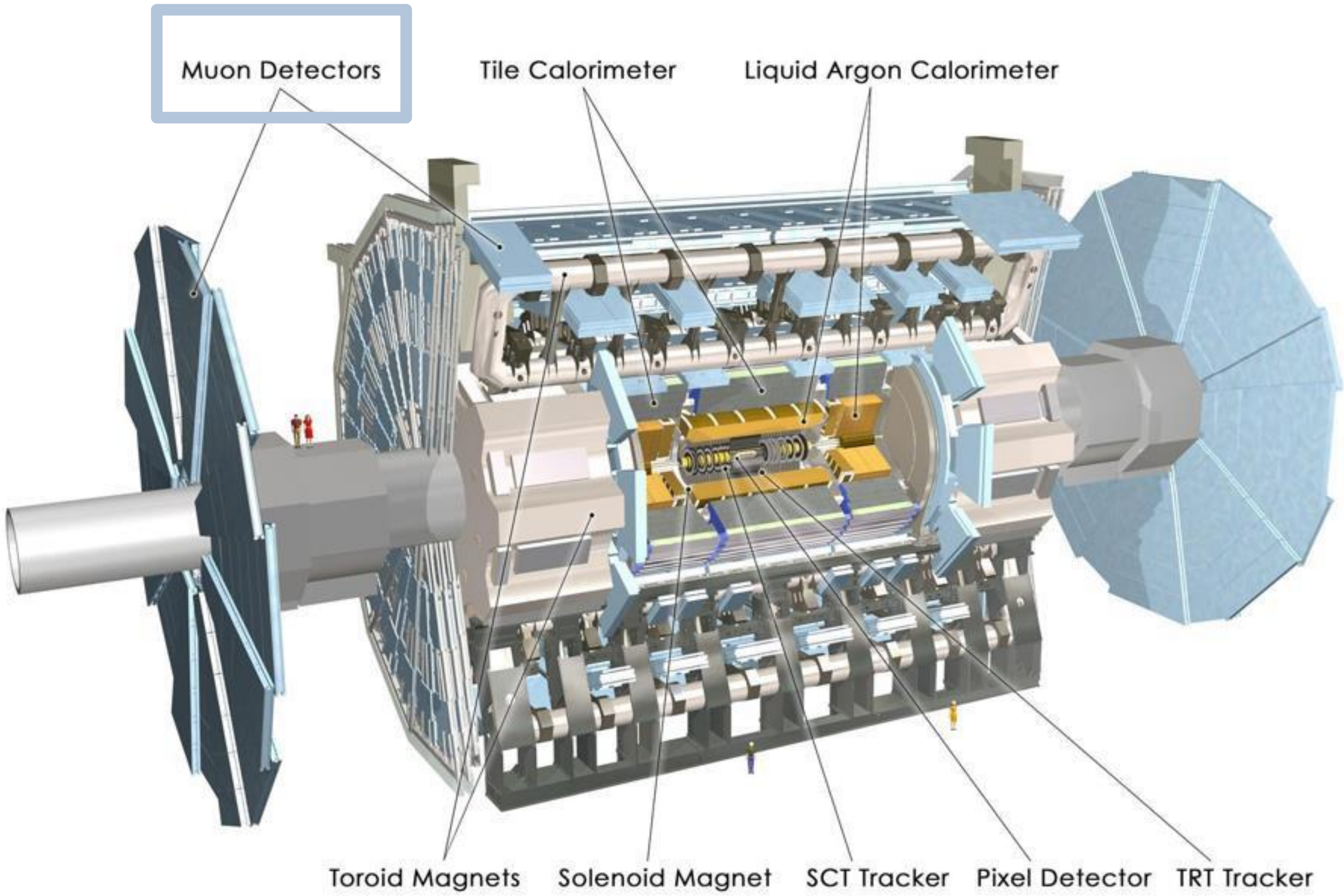

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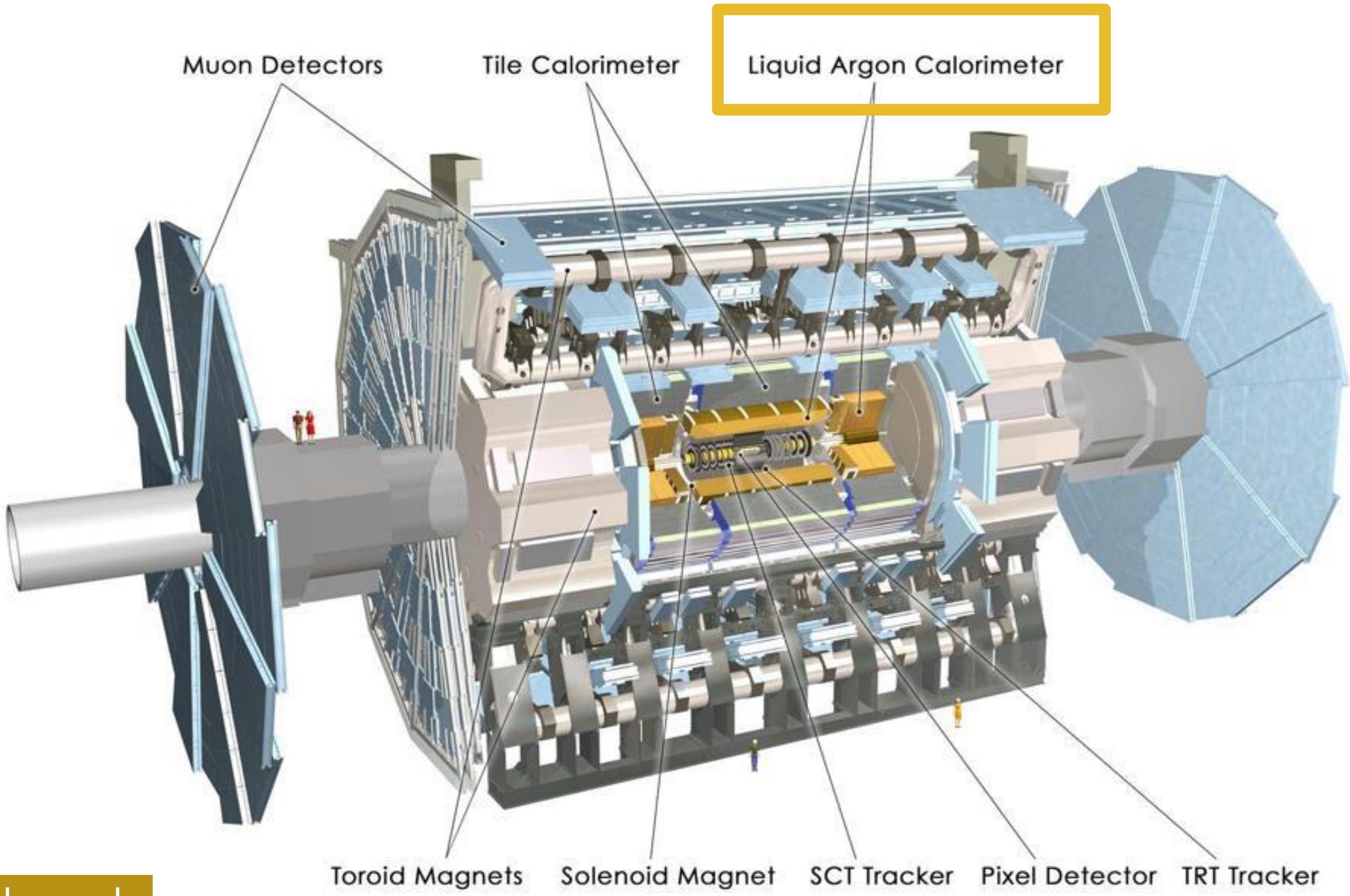
LArg; new FrontEnd and BackEnd electronics for faster readout
A new timing detector (HGTD) in the forward region



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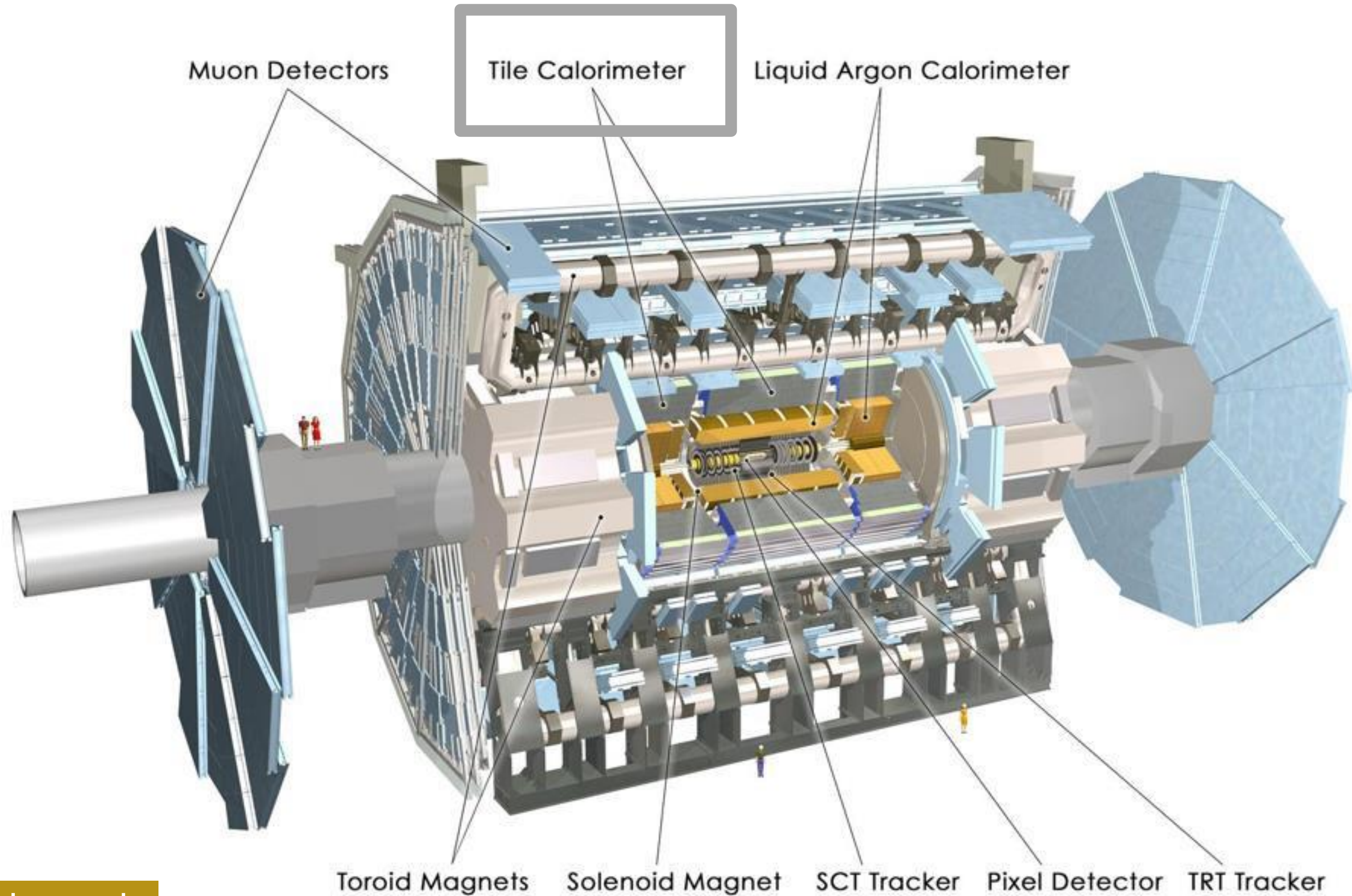

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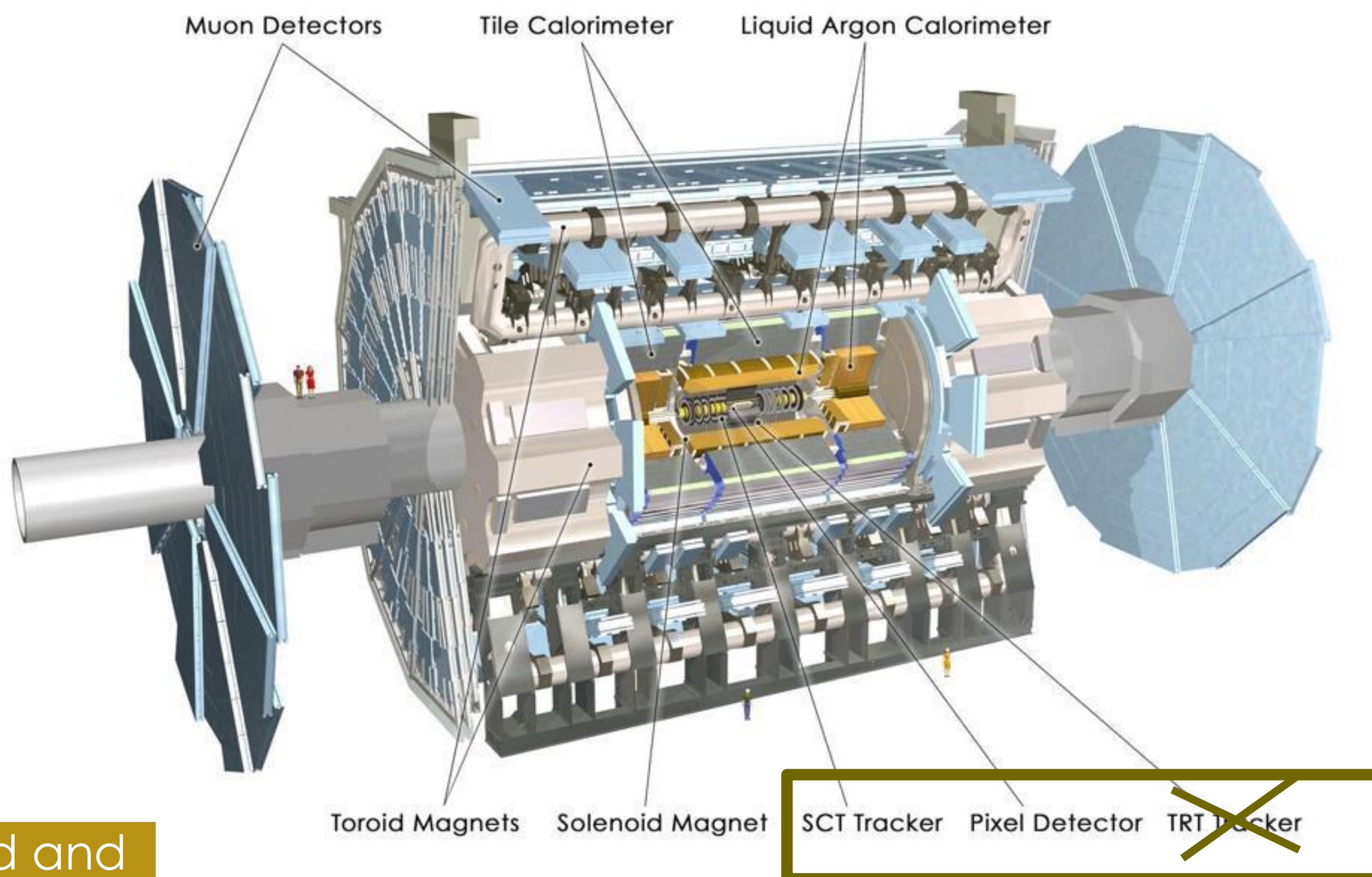

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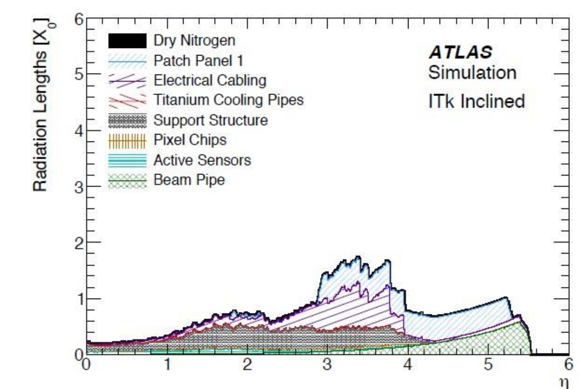
Inner Detector: full replacement by a all-silicon one (165m2), extending up to |η|=4
At most 1.75 X0



Tracker extension up to |η|=4 crucial for pileup rejection and VBF sensitivity

The ATLAS detector upgrade program

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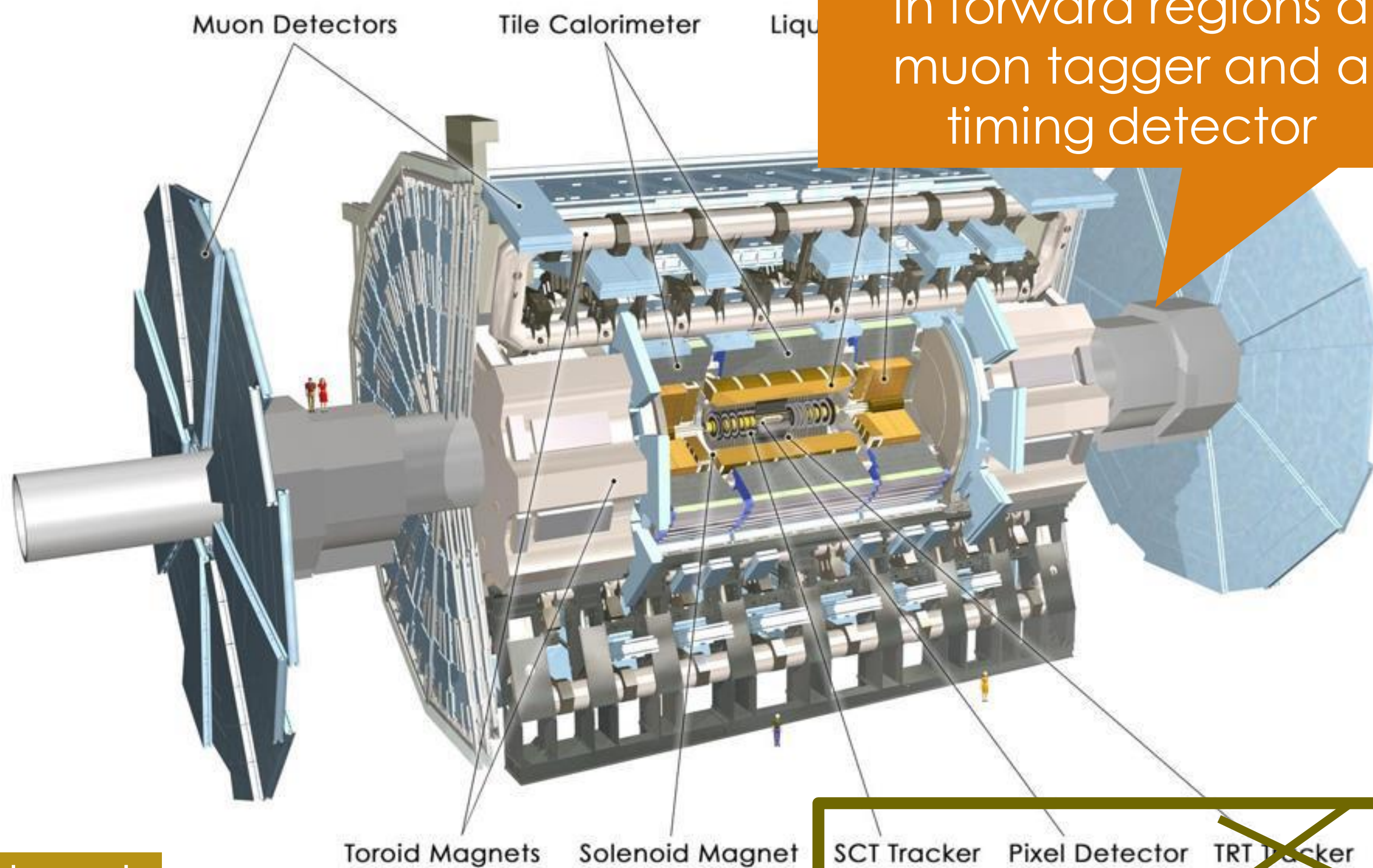

Discussions for adding in forward regions a muon tagger and a timing detector

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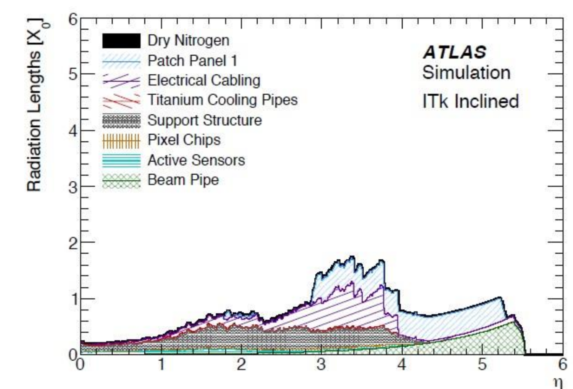
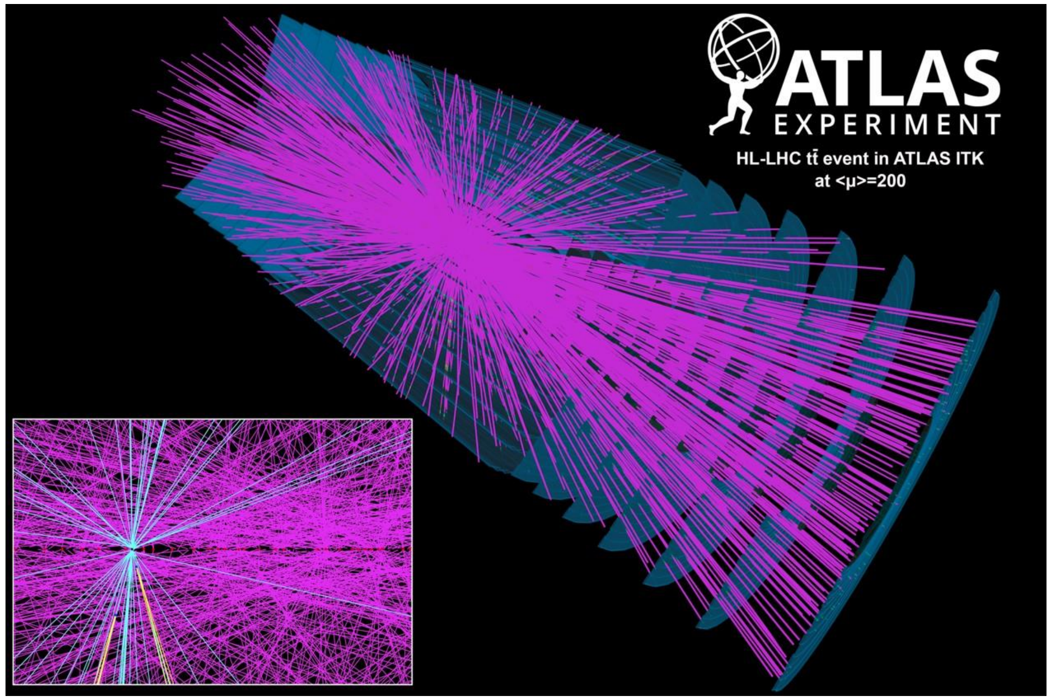


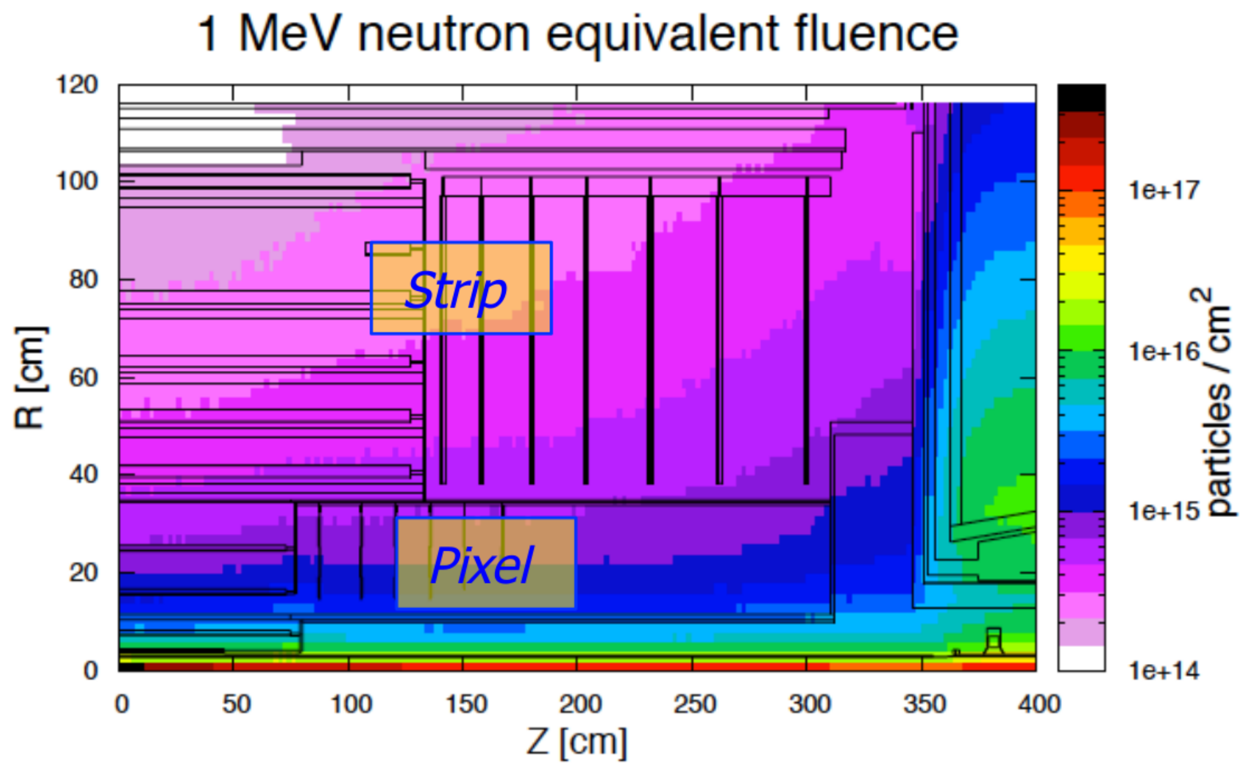
Tracker extension up to |η|=4 crucial for pileup rejection and VBF sensitivity

The ATLAS detector upgrade program

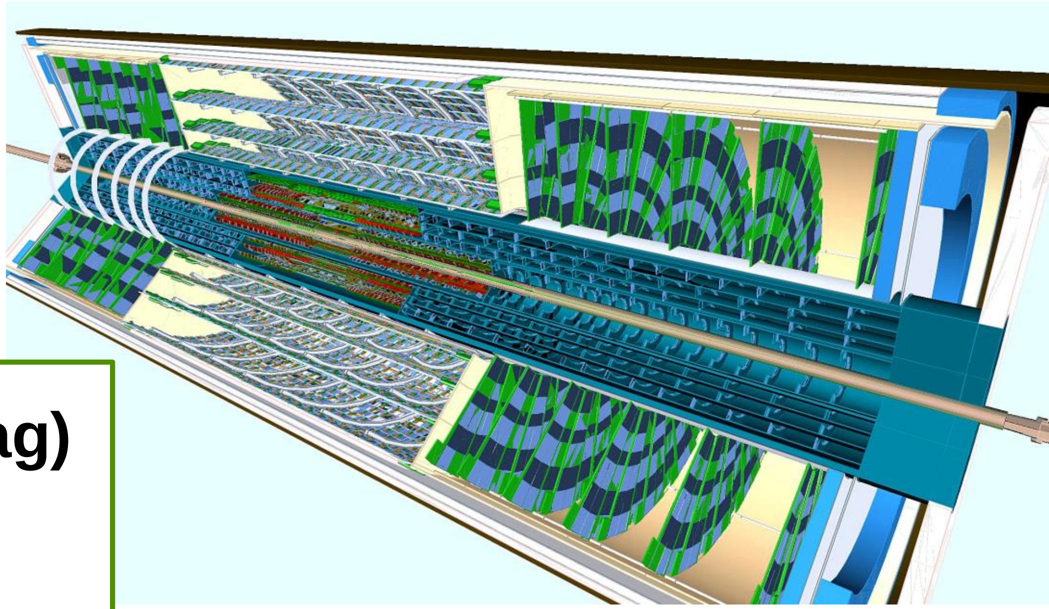
system	phase0 / run 2	phase 1 / run 3	phase 2 / run 4
Pixel	IBL at R=34 mm, new cooling, new services		replaced by ITk pixel
SCT			replaced by ITk strips
TRT			decommissioned
LAr	all new power supplies	new L1 trigger electronics	new readout electronics (input to L0Calo), 40 MHz streaming, High Granularity Timing Detector (HGTD)
Tile	new low voltage power supplies		readout electronics, 40 MHz streaming, improved drawer mechanics, new HV power supplies
RPC	gas leak repairs	BMG (sMDT) in acceptance gaps, BIS78 chambers between barrel and end-caps	new chambers in inner barrel
TGC		New Small Wheel (sTGC + MicroMegas)	new front-end electronics, forward tagger (option)
MDT			replace all front-end electronics
Trigger	new L1Topo, upgraded CTP, partial FTK L2 + EF → HLT	new FEX, full FTK, new muon-CTP interface HLT: multi-threading, offline-like algorithms	L0 (Calo, Muons) 1 MHz, 10 µs latency optional: L1 (L0 at 4 MHz, L1Track) 800 kHz, 35 µs latency
DAQ	custom hard-/firmware	FELIX for some systems	FELIX for all systems

The ATLAS new Inner TracKer (ITK)





- inst. Lumi. : 7.5 x 10^{34} cm^{-2} s^{-1}
- mean # of int. per bunch : $\langle\mu\rangle$ ~ 200 (high track density , high radiation)



- Performance (resolution , efficiency , Vertex → b-tag) to be maintained or better
- radiation tolerant

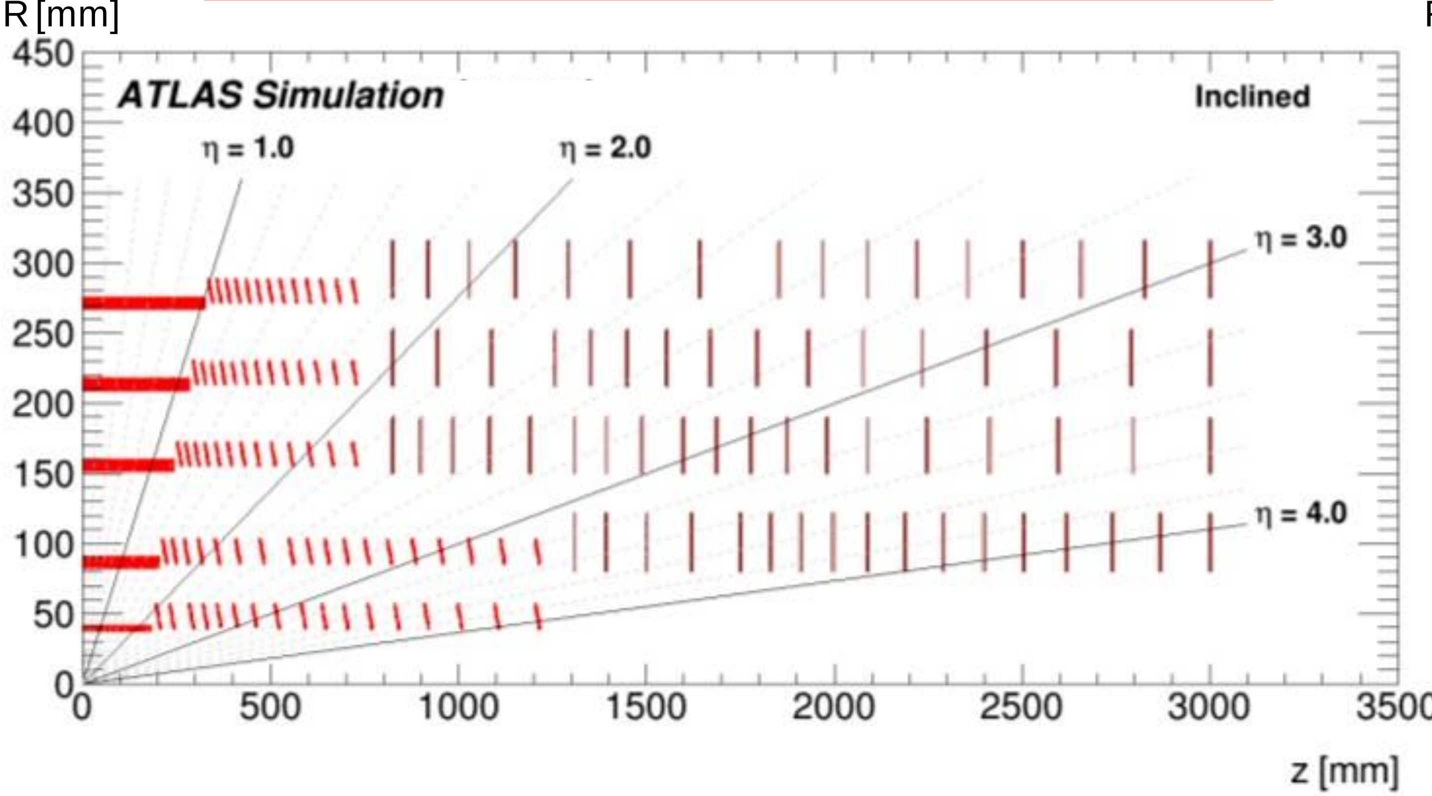
PIXEL & STRIP Layout

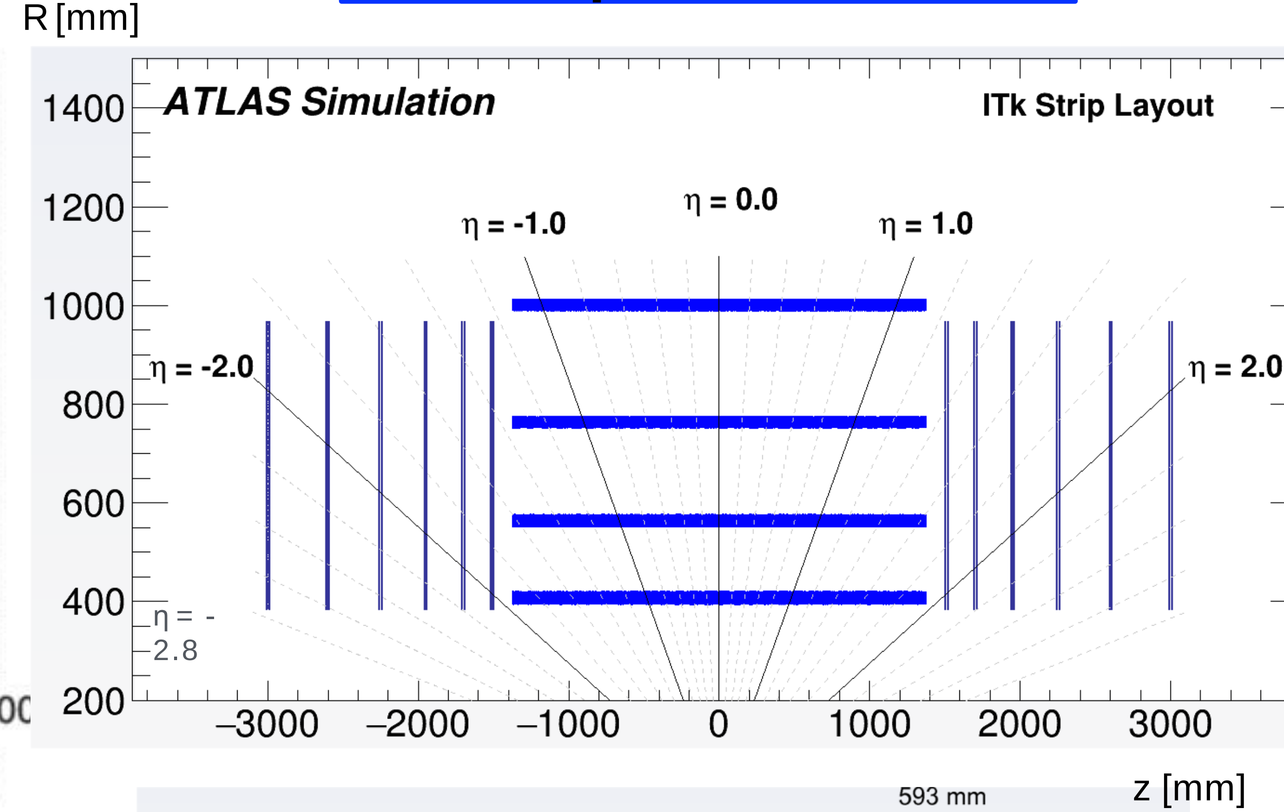
PIXEL

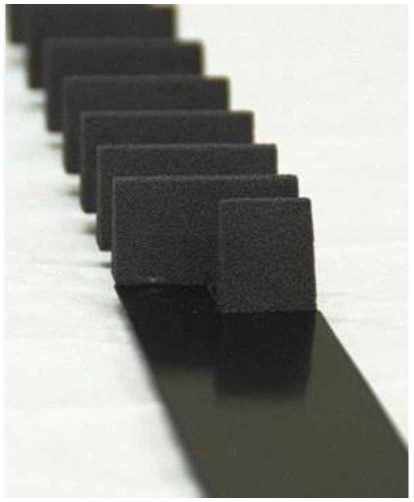
- **Barrel : 5 layer**
- **Endcap : inclined modules + Rings**

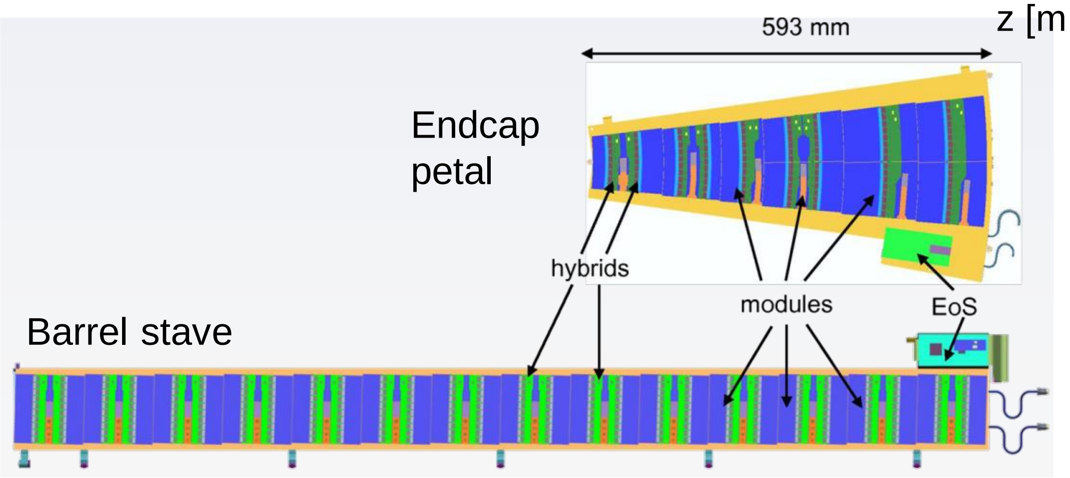
STRIP

- **Barrel : 4 layer**
- **Endcap : 6 Disks x 2**





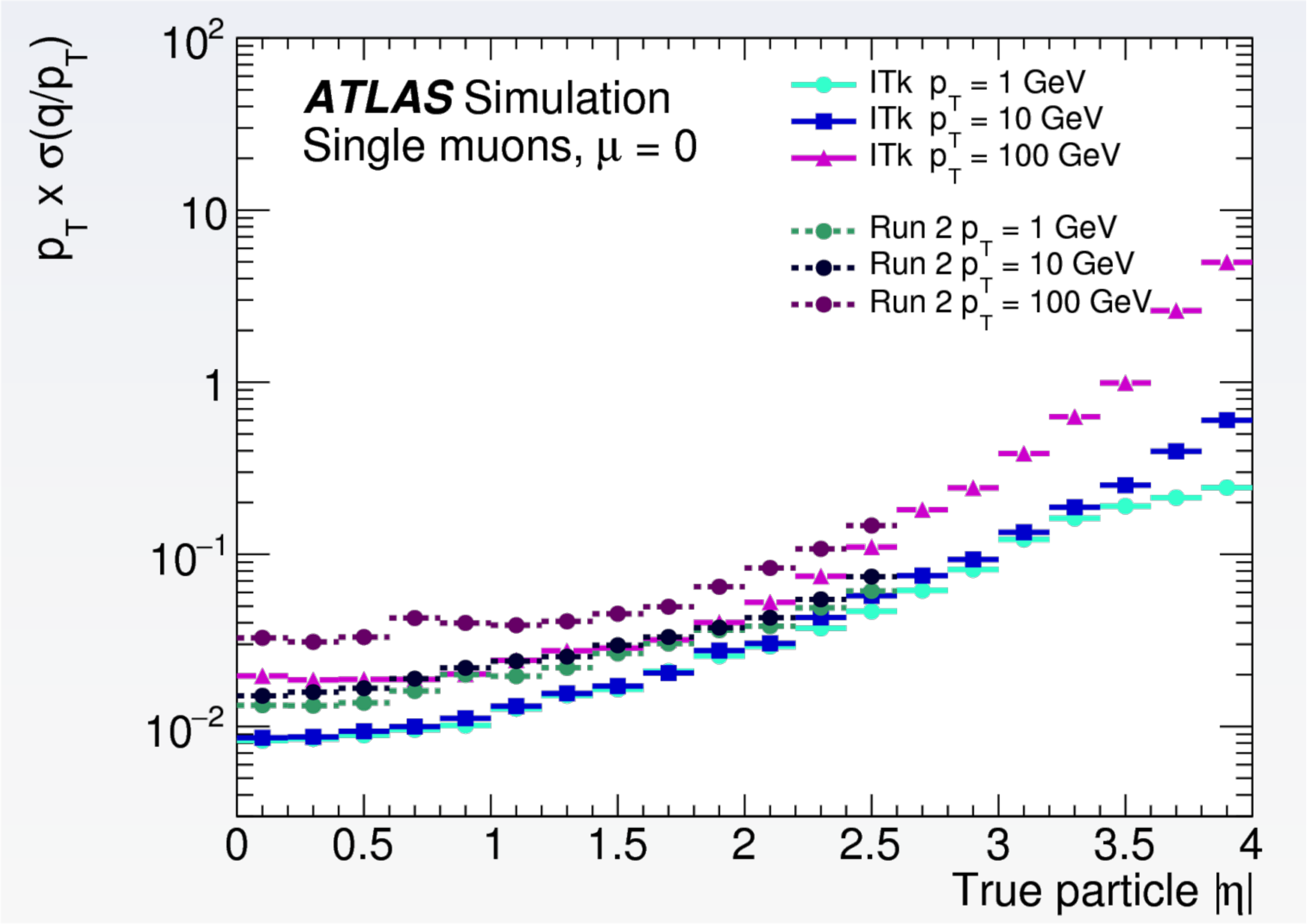




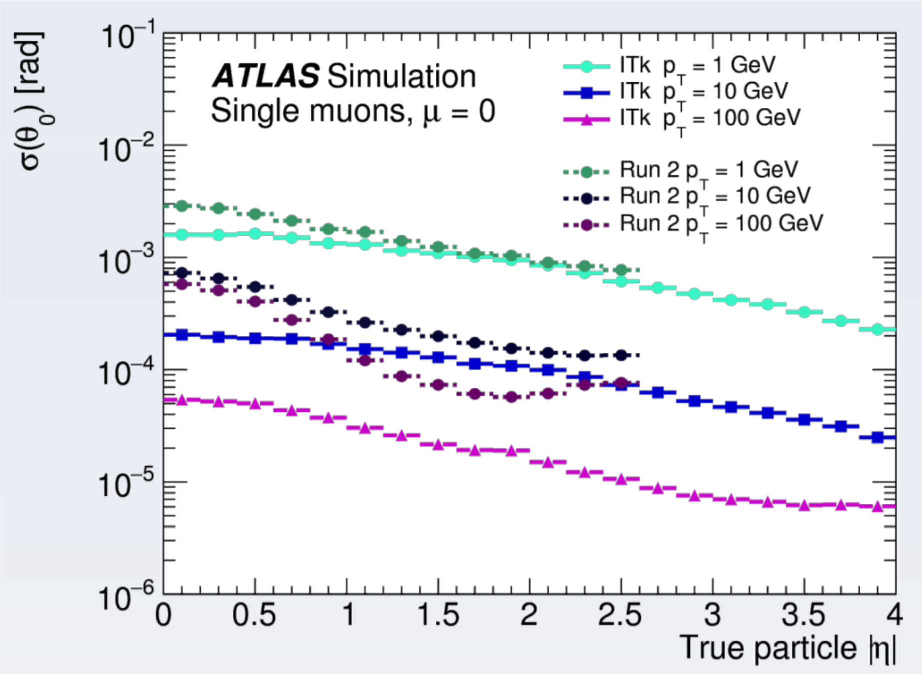
- **R < 1m ; all Silicon sensor**
- **| η | < 4.0 (NEW : 2.5 < |η| < 4.0)**

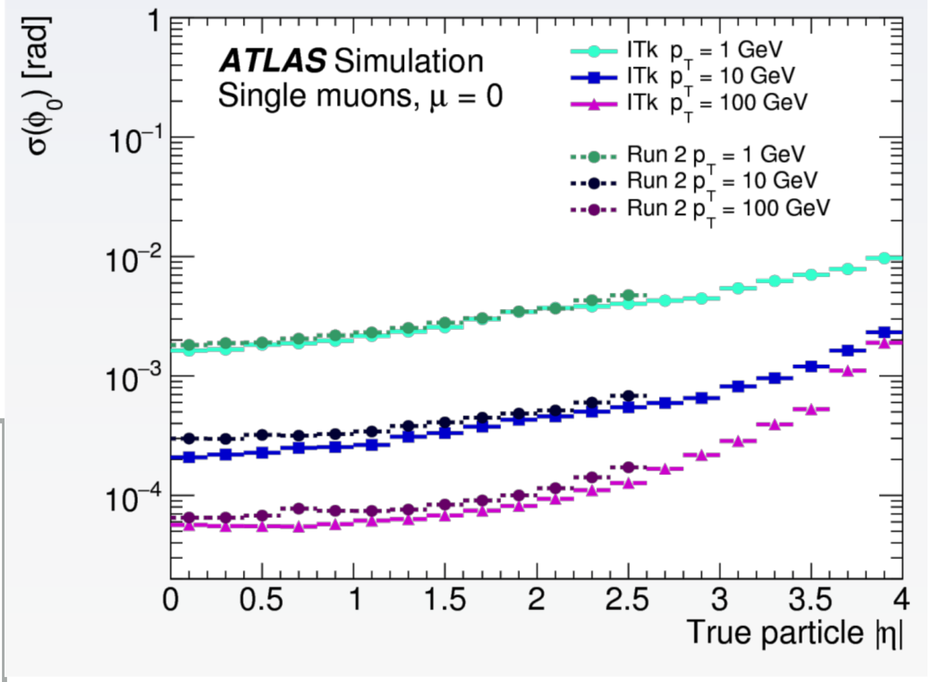
Performance: resolution (p_T , θ_0 , φ_0)

momentum resolution



angular resolution





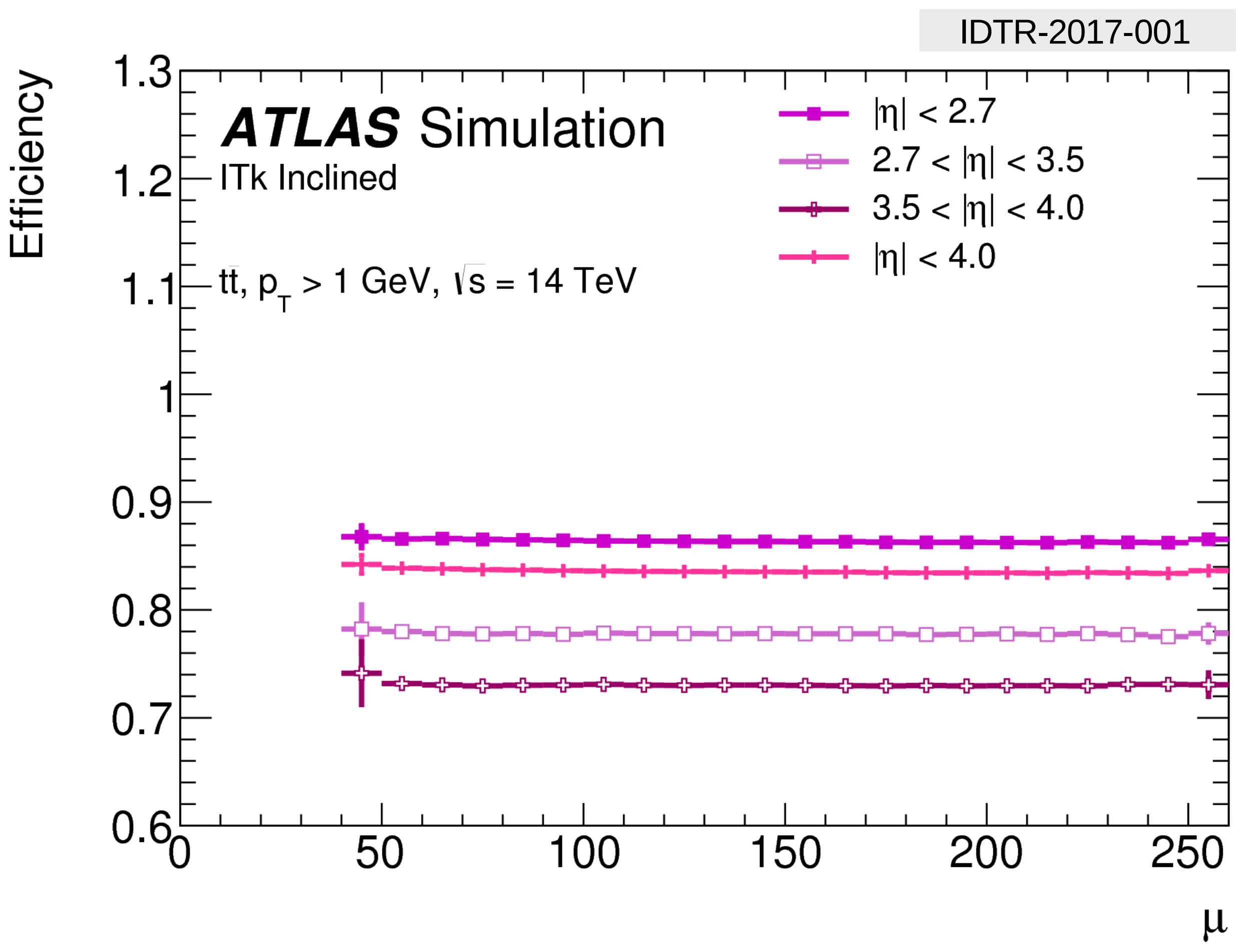
estimation : using single-μ tracks

large improvements [p_T , θ_0] w.r.t. the current system

(the coverage up to $|\eta| < 4.0$)

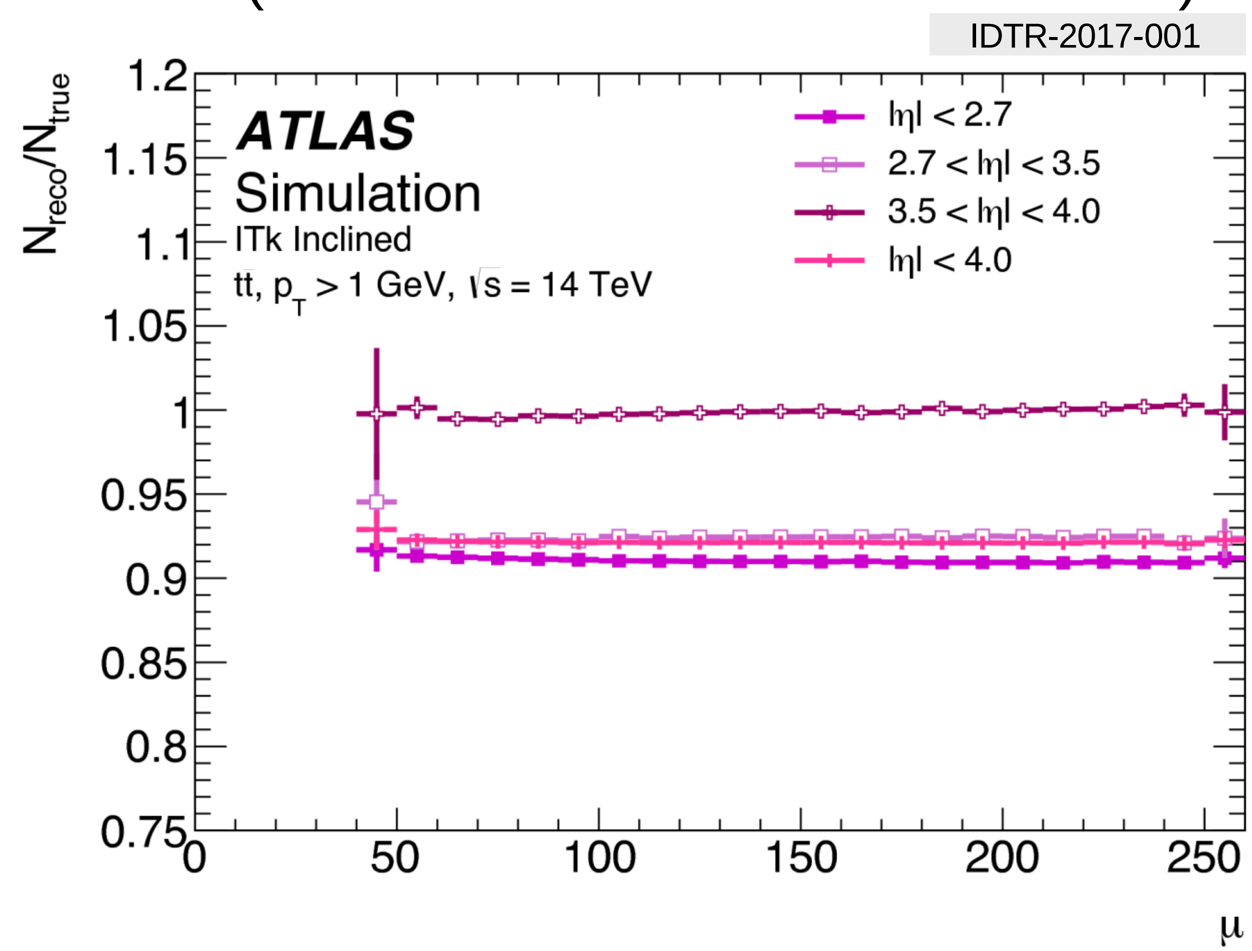
Performance: Pile-up (< μ >) dependence

tracking efficiency



fake track ratio

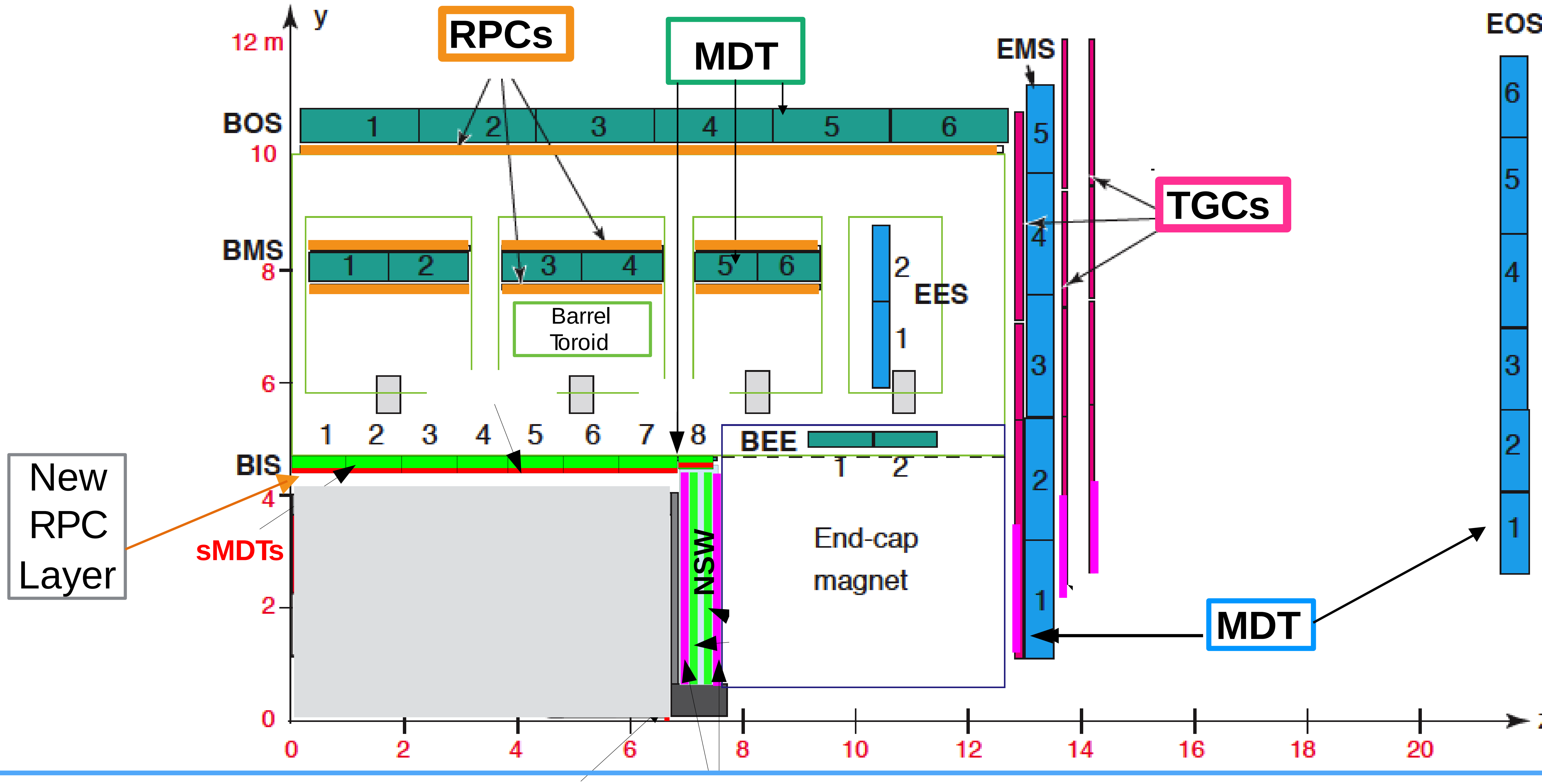
(# of redo. tracks / # of truth tracks)



the tracking efficiency is (almost)
unchanged up to μ=250 for all the |η| regions

mostly independent to <μ>
no problem with fakes up to μ = 250

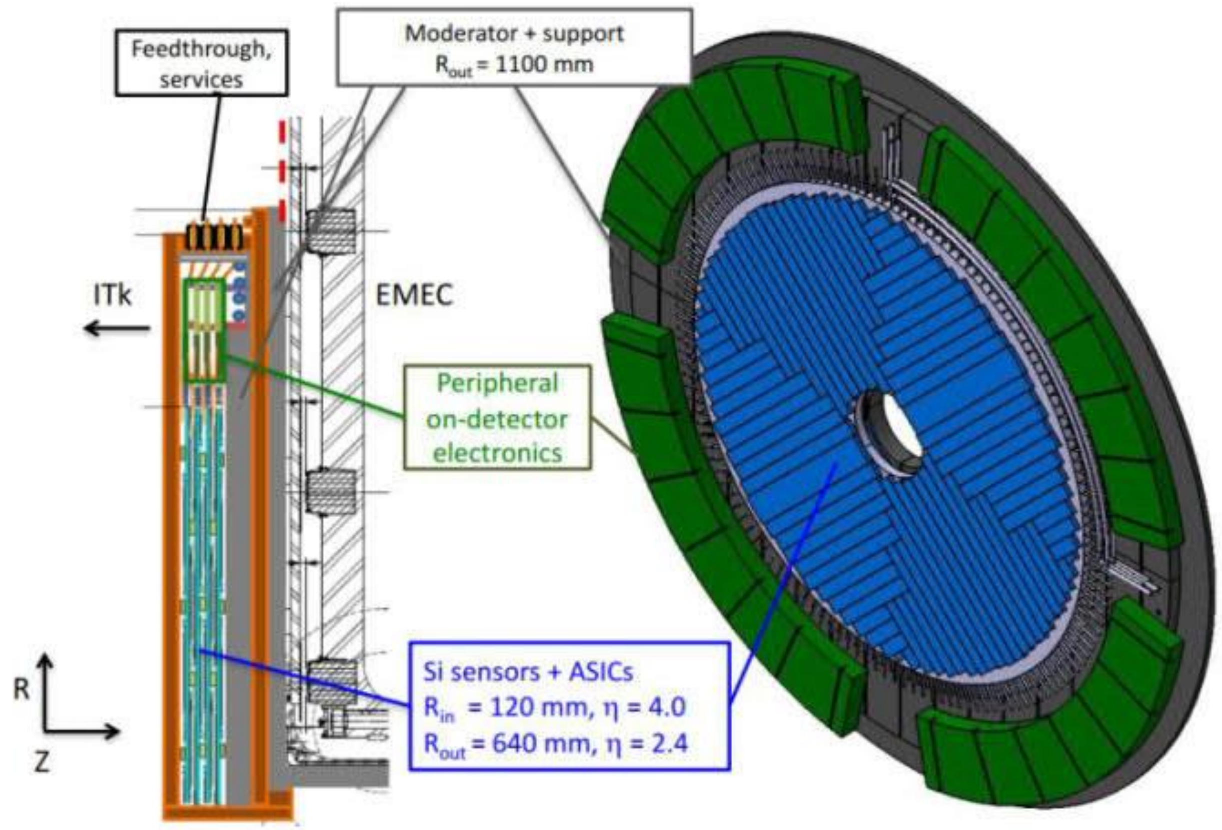
The ATLAS muon system



- A complex of **Trigger** chamber (RPC / TGC + NSW) and Precision **tracker** (MDT, NSW)
- Cope with longer latency & higher trigger rate, **all the electronics to be replaced**
- **MDT** (max. Drift-Time ~ 700ns) to be a part of **Hardware μ-Trigger**
- **ALL the hits** of TGC/RPC/MDT sent to off-detector → process Trigger

The High Granularity Timing Detector

- Precise assignment of tracks to Hard-Scatter (HS) vertex → to mitigate the pileup effects
  - **Space separation** of vertices in the beam direction (z)
    - High pile-up density at HL-LHC
    - σ_{z_0} is not good in the forward region
  - **Time separation of vertices**

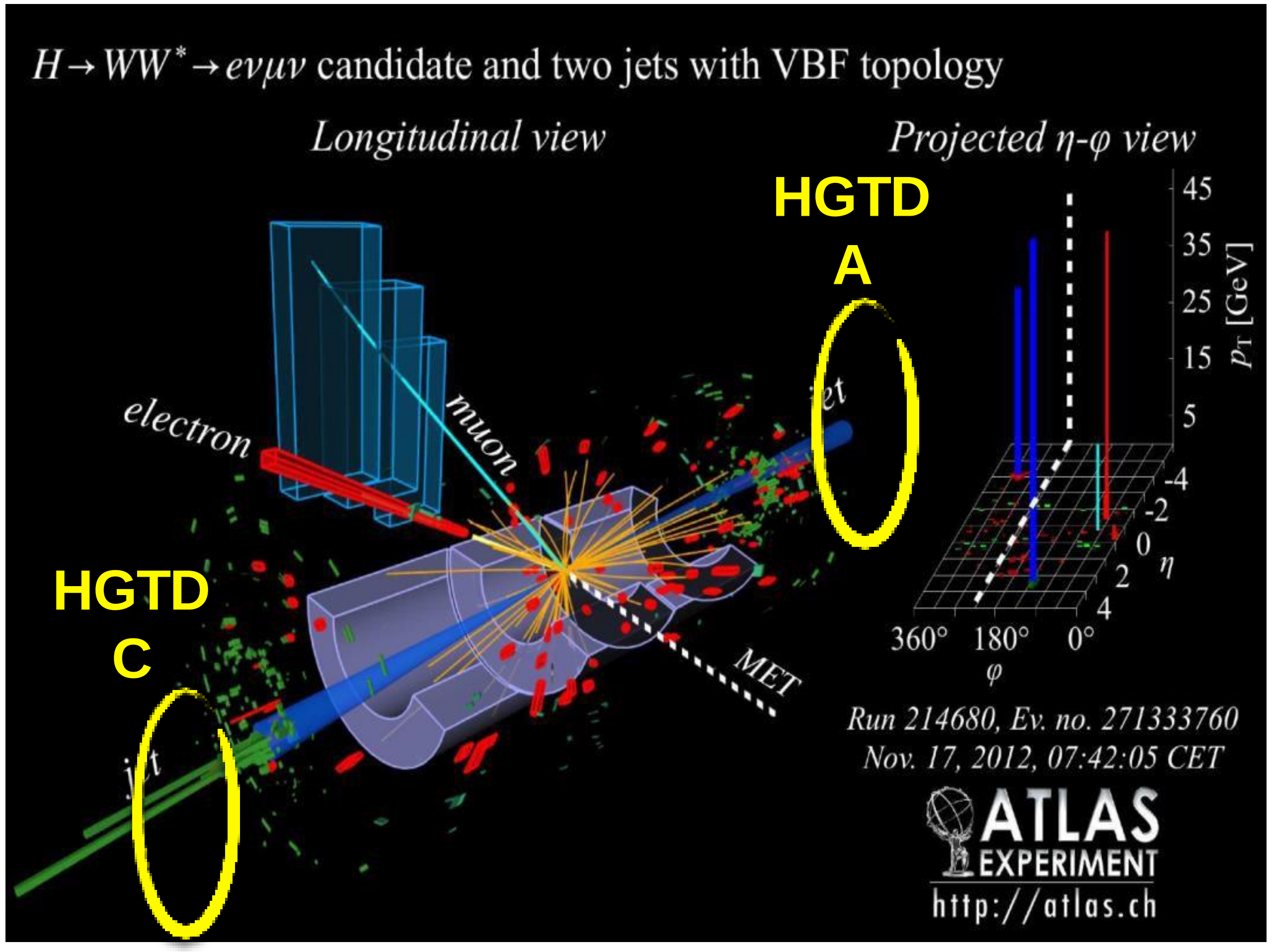


HGTD

- Designed to distinguish between **collisions occurring very close in space but well separated in time**
- Located just outside of ITk covering the forward region $\mathbf{2.4 < |\eta| < 4.0}$
- Consisting of 4 silicon layers
  - 10% occupancy in $1.3 \times 1.3\ \mathrm{mm}^2$ pixels
- Expected **timing resolution of 30 ps** will greatly improve the track-to-vertex association in the forward region
  - Compared to 180 ps RMS spread of collisions

HGTD Motivation

Important EW channels



- ✓ Potential of HGTD as a L (40MHz) Time trigger for the VBF 0channel
- ✓ Lower jet P_T thresholds and extend accessible phase space
- ✓ Largest potential in hadronic final state VBF channels (also offline), preferentially forward peaked:

$$H \to bb,\ H \to Inv.,\ HH \to bbbb$$

- Pre-shower option :
  - ➢ Improve forward electron/photon reconstruction
  - ➢ Interesting for search in

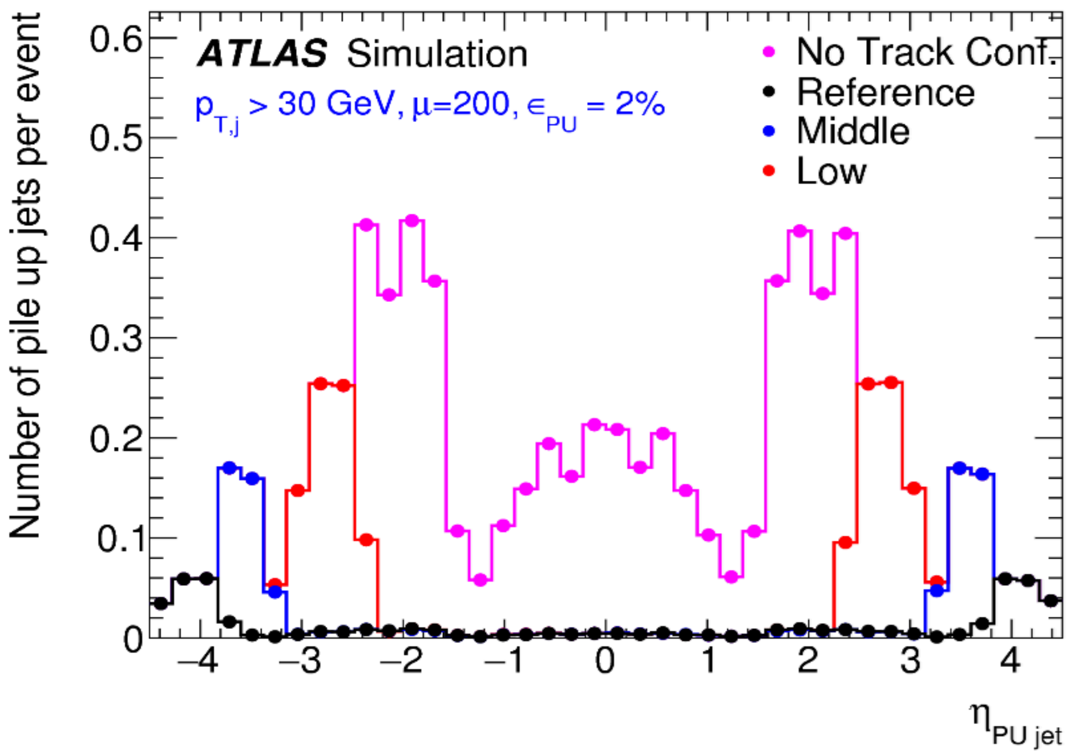
$$H \to aa \to \gamma\gamma jj$$

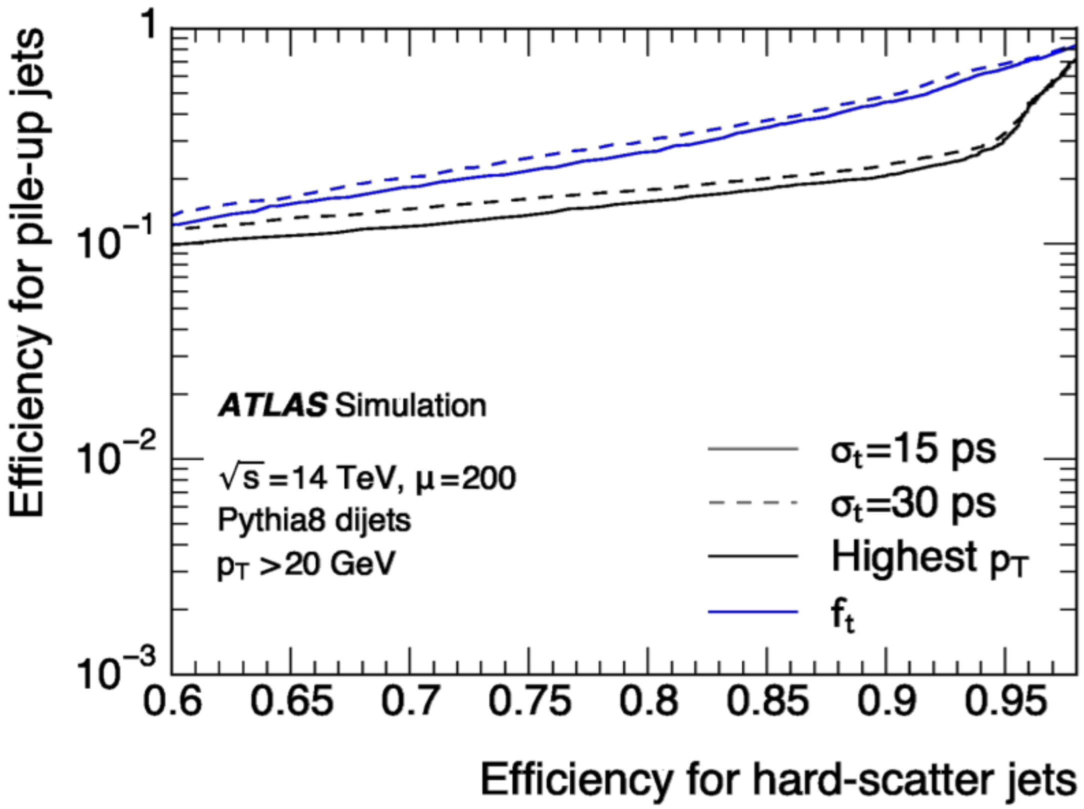
Trigger	SD value	physics
di-γ	25-25 GeV	di-photon
di-τ	40-30 GeV	H→ττ
4-jet	75 GeV	H→bb, HH→4b
E_T^{miss}	200 GeV	H→Inv.

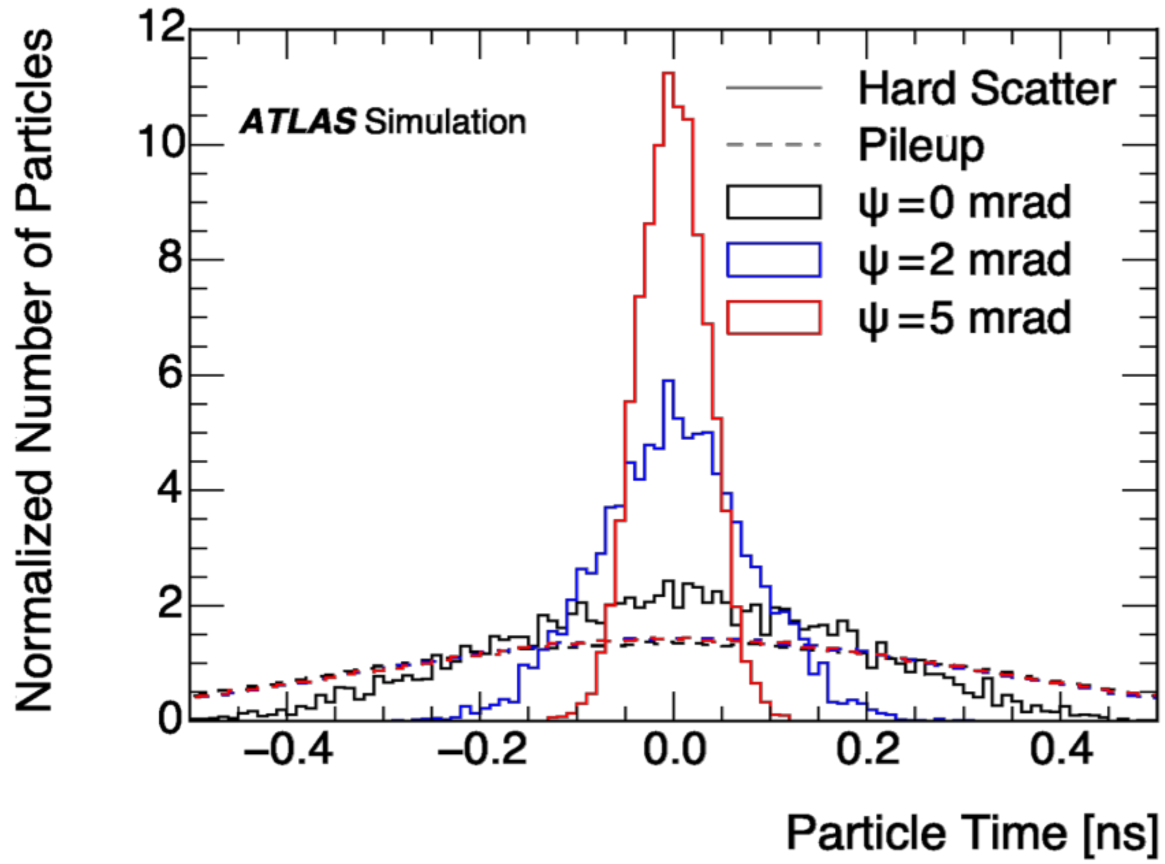
The High Granularity Timing Detector

Time – Pileup Rejection

- ✓ High probability of vertices in close proximity
- ✓ Time information helps pileup rejection
- ✓ Pileup distribution extremely peaked at forward 1.8 <$|\eta|$< 3.2 were tracker not completely implemented
- ✓ Track confirmation rejection at 2% for central region but degrades towards end caps



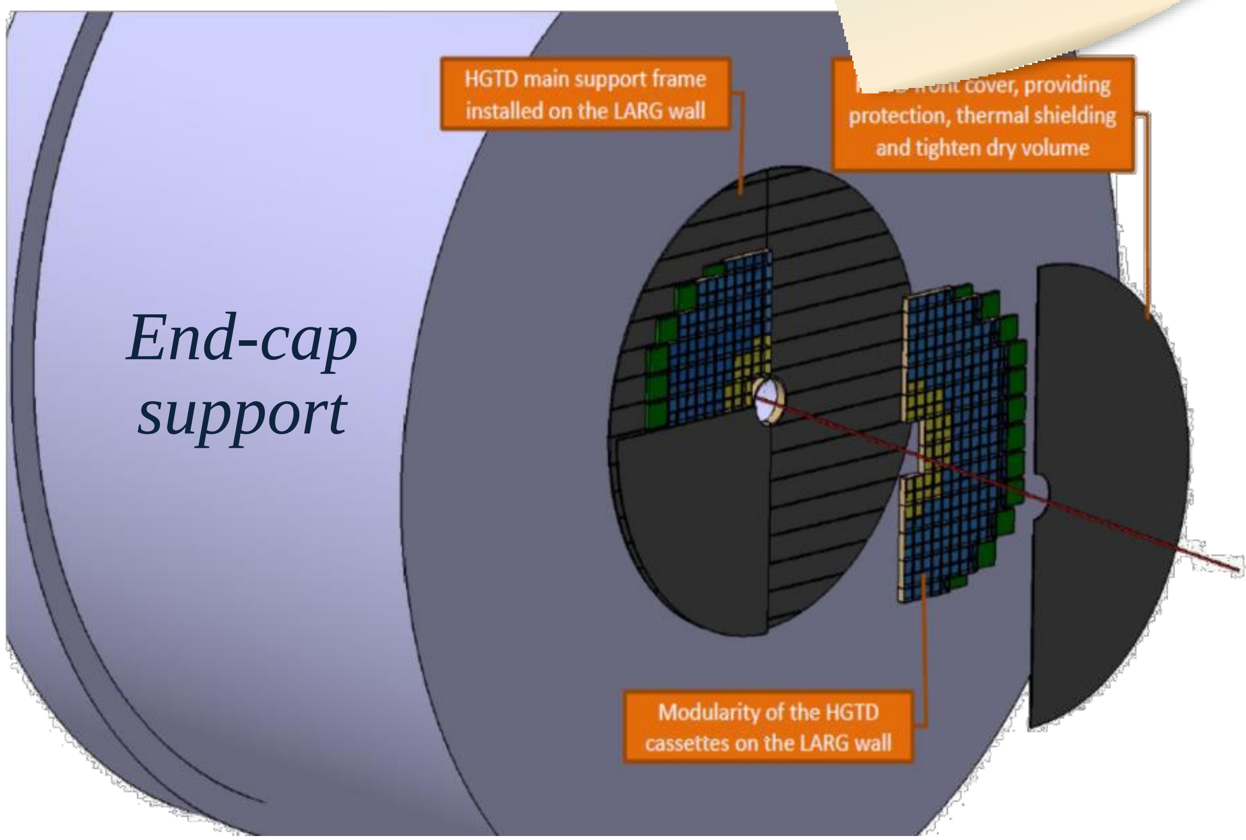


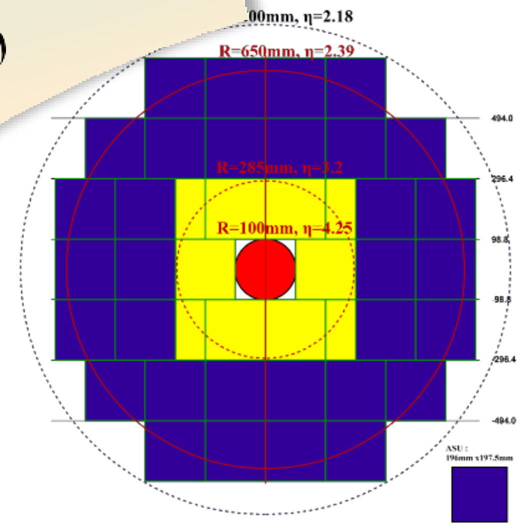


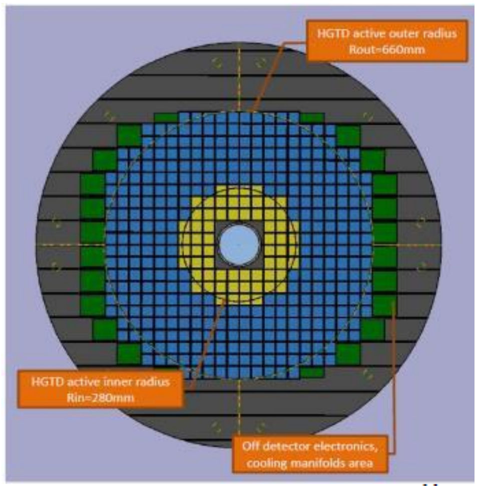
HGTD System

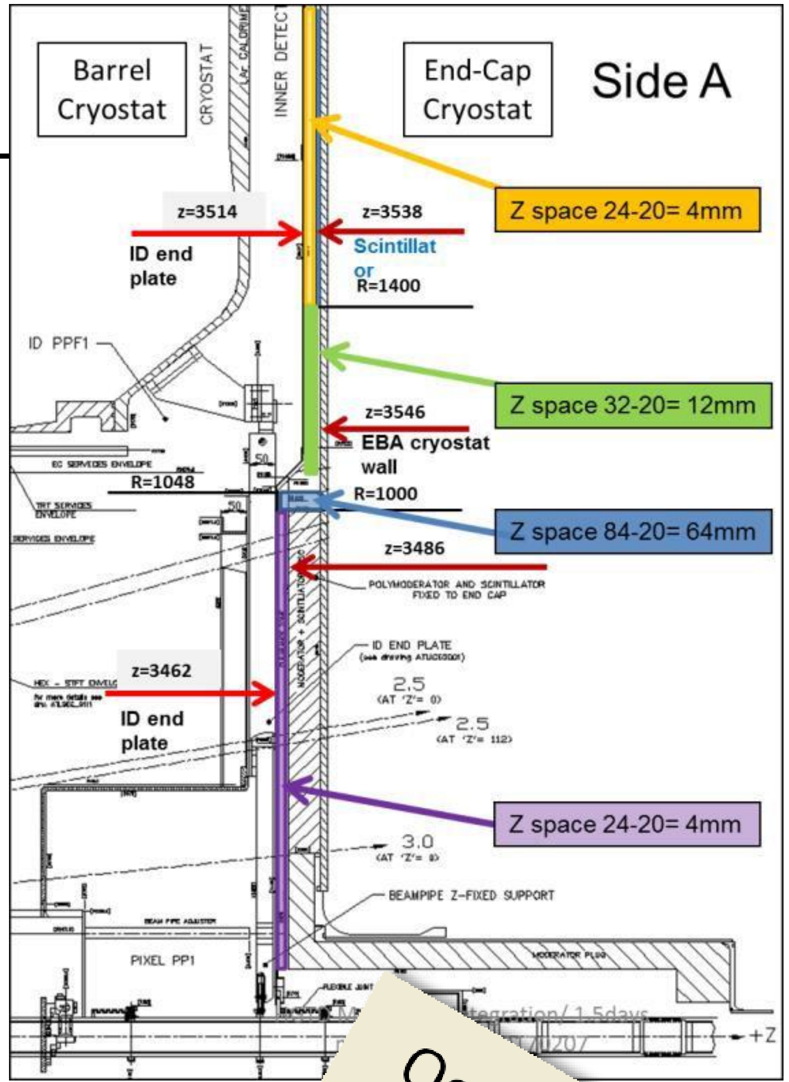
Geometry

- HGTD-Si: 4 si layers
- HGTD-SiW: 4 si layers + $3X_0$ W $2.4 < \eta < 3.2$ (R_{min}=285mm)

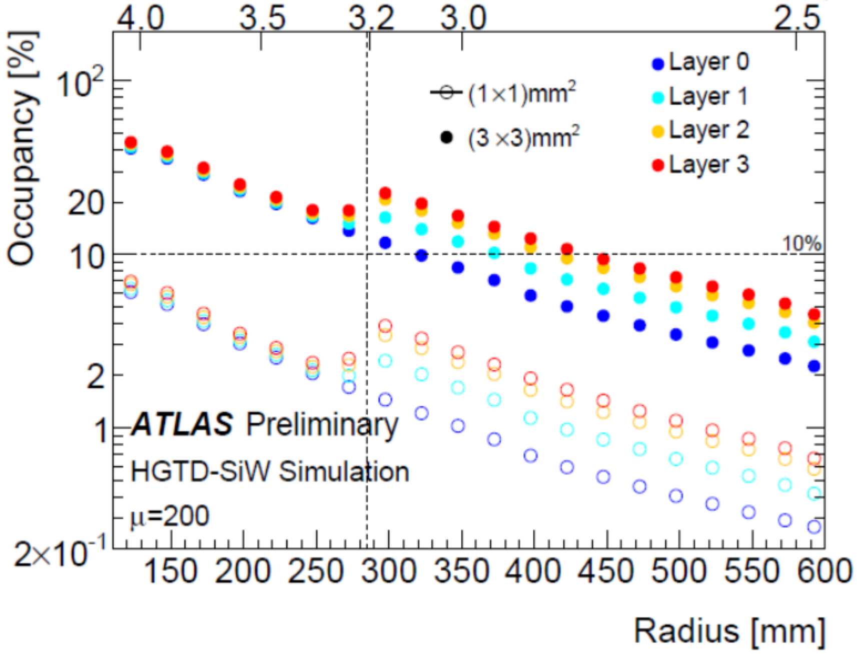




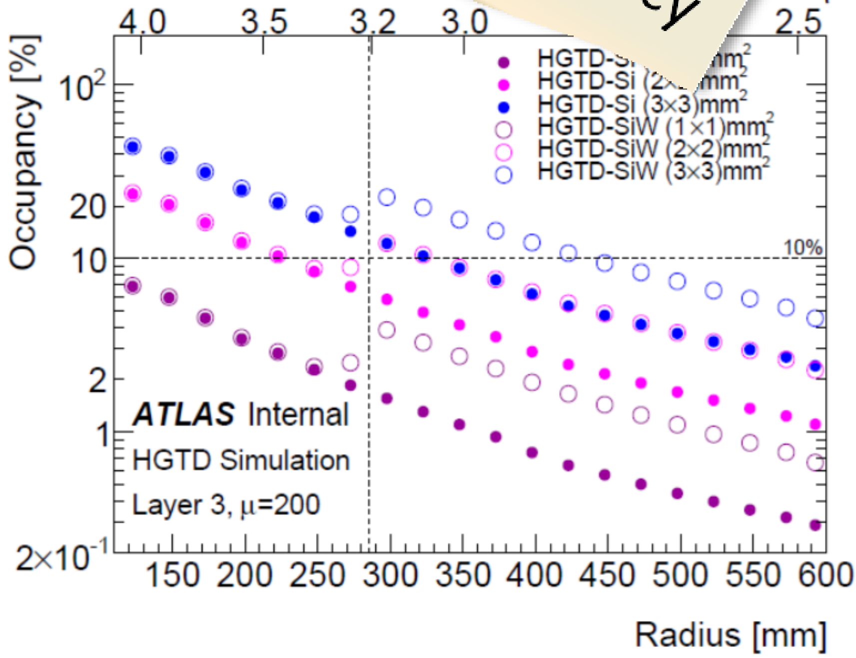




Specifications for 2023	
Coverage	$2.4 < \eta < 4.2$
R_{min}	11 cm
R_{max}	65 cm
Δz	~ 6 cm
Δt	< 50 ps
Cell Size	1 mm²



Occupancy

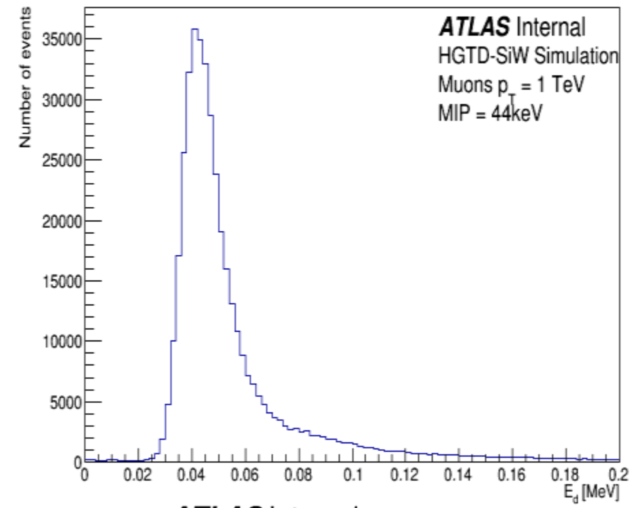


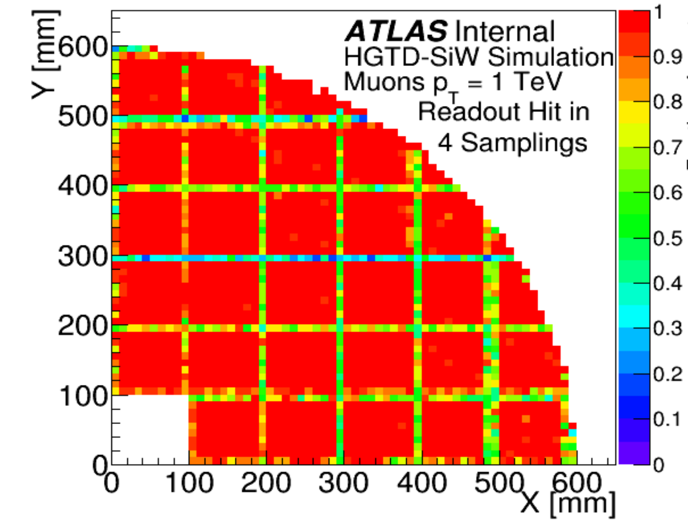
HGTD performance for objects reconstruction

Performance

Muons

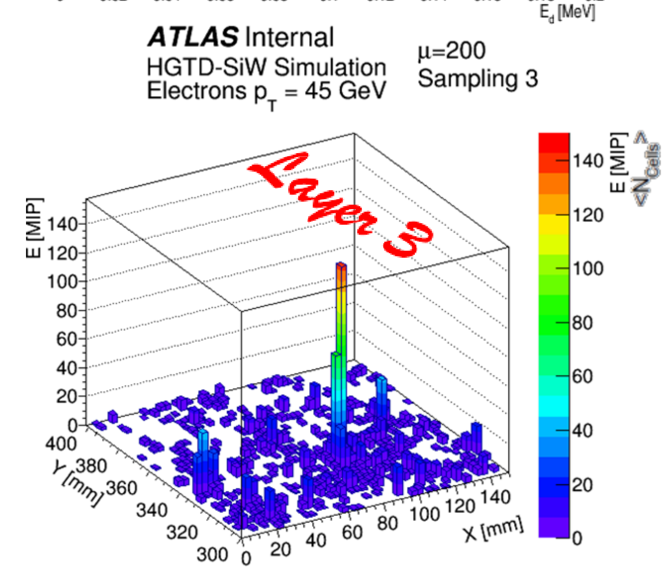
- ✓ 1TeV muons simulation
- ✓ 98.88% efficiency for 4 layers
- ✓ 0.044 MeV/muon at 150 μm
- ✓ 50% of inefficiency from zones

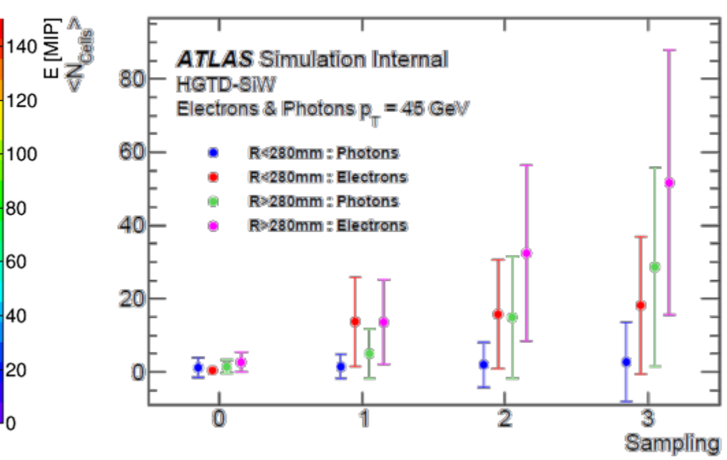




Electrons

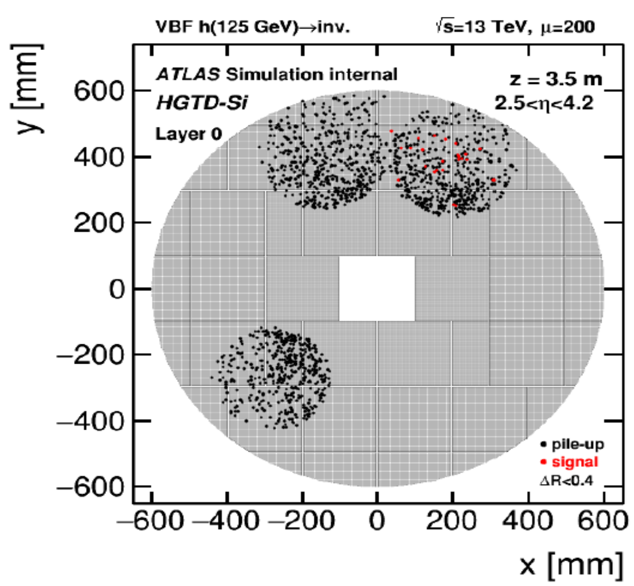
- ✓ Z → ee sample at μ = 200
- ✓ 45 GeV P_T e and γ
- ✓ 6mm radius EM clusters
- ✓ 70 HGTD cells per cluster
- ✓ Dynamic range of 50psec/MIP

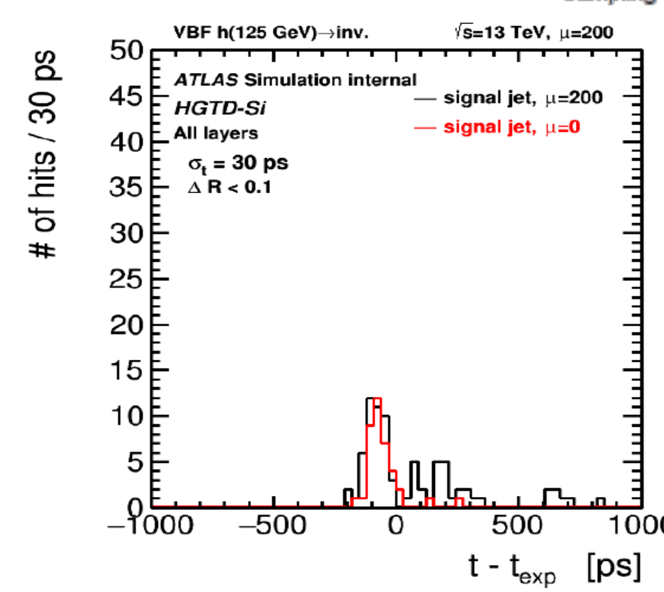




Jets

- ✓ H(125GeV) → Inv. sample with jet P_T=72GeV
- ✓ Expected peak in time distribution
- ✓ ~90% signal purity at ΔR < 0.1





ATLAS Trigger and Data Acquisition Upgrades

L0 trigger (baseline):

- Hardware trigger based on calorimeter and muon information
- MDT precision information available
- Global event processor refines e, γ, τ, jet and E_T^{miss} objects
- 1 MHz rate at 10 μs latency

Option: dual L0/L1 trigger:

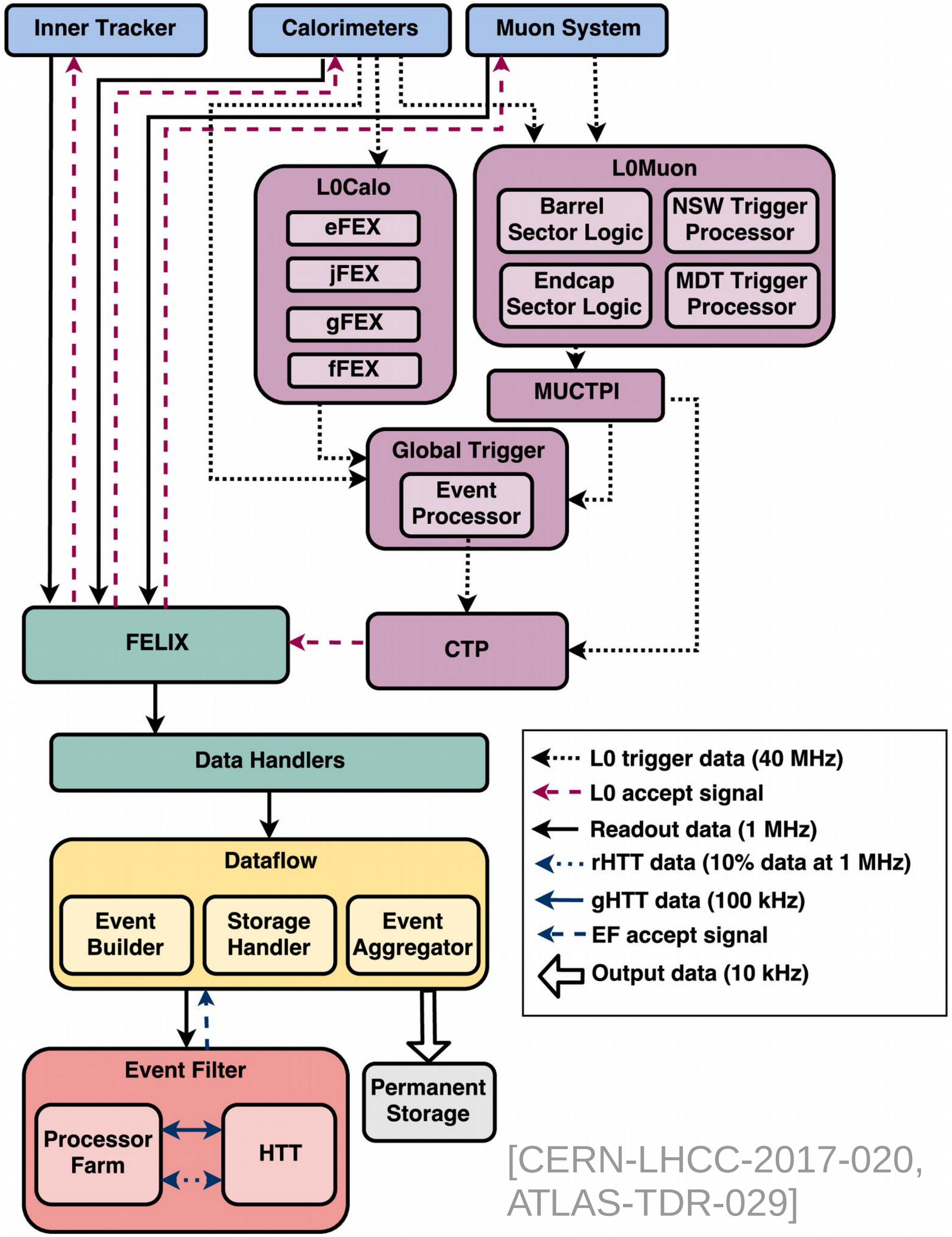
- 4 MHz rate at 10 μs latency
- Hardware tracking (L1track) → pileup suppression

Data Acquisition:

- Front End LInk eXchange (FELIX)
- New Storage Handler

Event Filter:

- Hardware Track Trigger (HTT) → 400 kHz
- High-Level-Trigger (HLT) in software → 10 kHz



[CERN-LHCC-2017-020, ATLAS-TDR-029]

Trigger Menu @ ATLAS (HL-LHC)

HL-LHC @ 7.5x10^{34}	Offline p_T Threshold [GeV]	Offline $\|\eta\|$	**L0** Rate [kHz]
isolated Single e	22	< 2.5	200
forward e	35	2.4 – 4.0	40
single γ	120	< 2.4	66
single μ	20	< 2.4	40
di-γ	25	< 2.4	8
di-e	15	< 2.5	90
di-μ	11	< 2.4	20
e – μ	15	< 2.4	65
single ☒	150	< 2.5	20
di-☒	40,30	< 2.5	200
single jet	180	< 3.2	60
fat jet	375	< 3.2	35
four-jet	75	< 3.2	50
H_T	500	< 3.2	60
E_T^{miss}	200	< 4.9	50
jet + E_T^{miss}	140,125	< 4.9	60
forward jet	180	3.2 - 4.9	30
Total			**1MHz**

ex : single-lepton

	Run-1	Run-2	**HL-LHC**
	0.8 x10^{34}	2.0 10^{34}	**7.5 10^{34}**
1e	25 GeV	32	**22 GeV**
1μ	25 GeV	27	**20 GeV**

Aim : **similar threshold as Run-1** & **Larger Geom. acceptance**

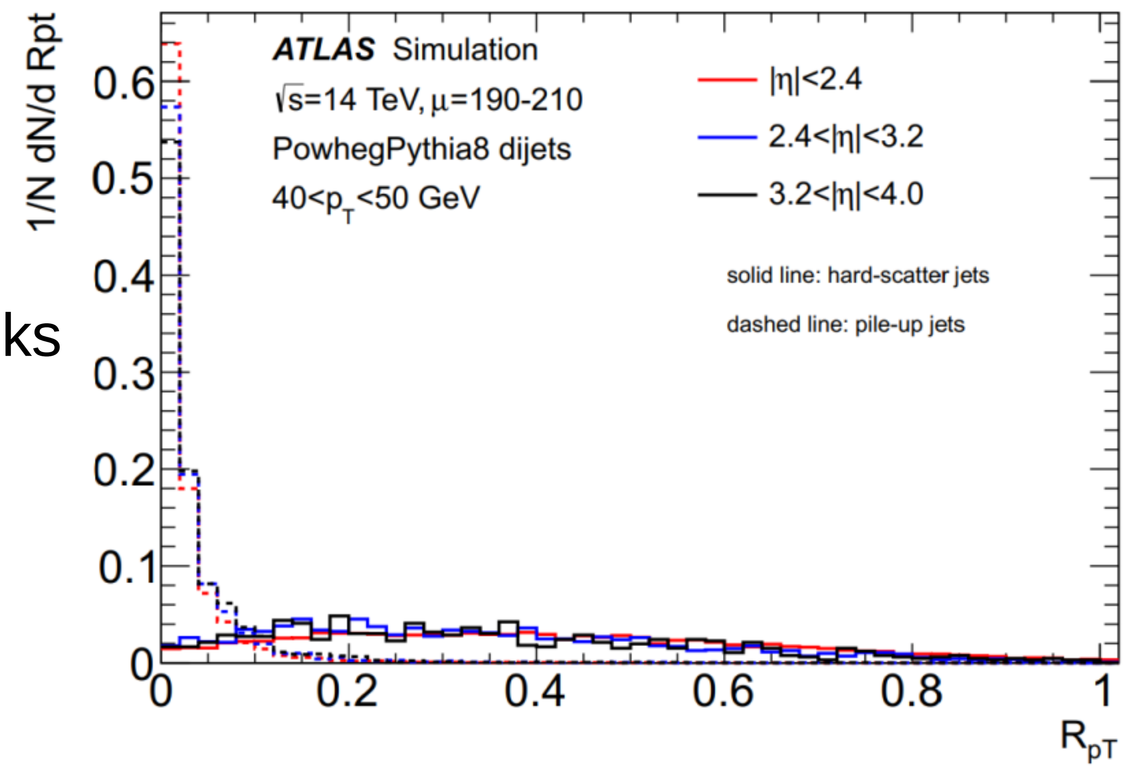
Examples of expected Physics Performances of the ATLAS at the HL-LHC

Pile-up Jets Suppression

- **Pile-up jet tagging** with the discriminant

$$R_{p_T} = \frac{\sum_k p_T^{\mathrm{trk}_k}(\mathrm{PV}_0)}{p_T^{\mathrm{jet}}}$$

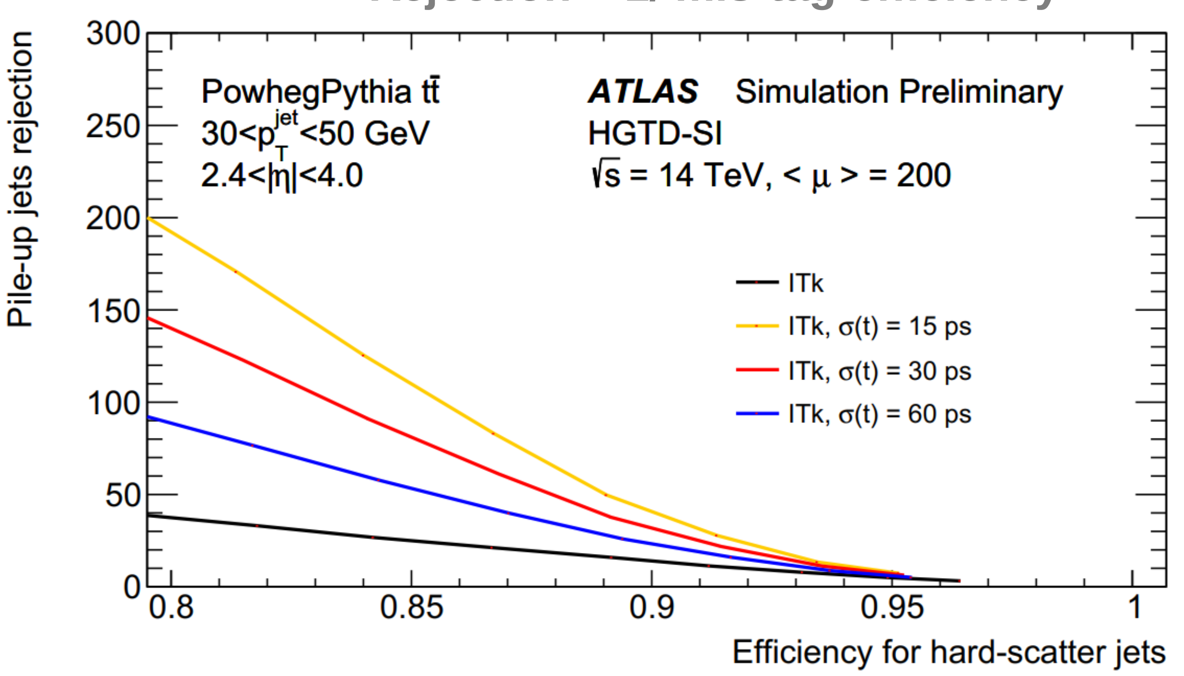
  - Defined as the scalar sum of the □□$_T$ of all tracks within a jet associated with the HS vertex, divided by the jet p_T
  - **Small value of R_{pT} for pile-up jets**



- Rejection vs efficiency as a scan over the R_{pT} requirement

- **Significant improvement of pile-up jet rejection in the forward region**
  - **Extended coverage of ITk**
    - **Track-based pile-up suppression**
  - **HGTD**
    - **Timing information**

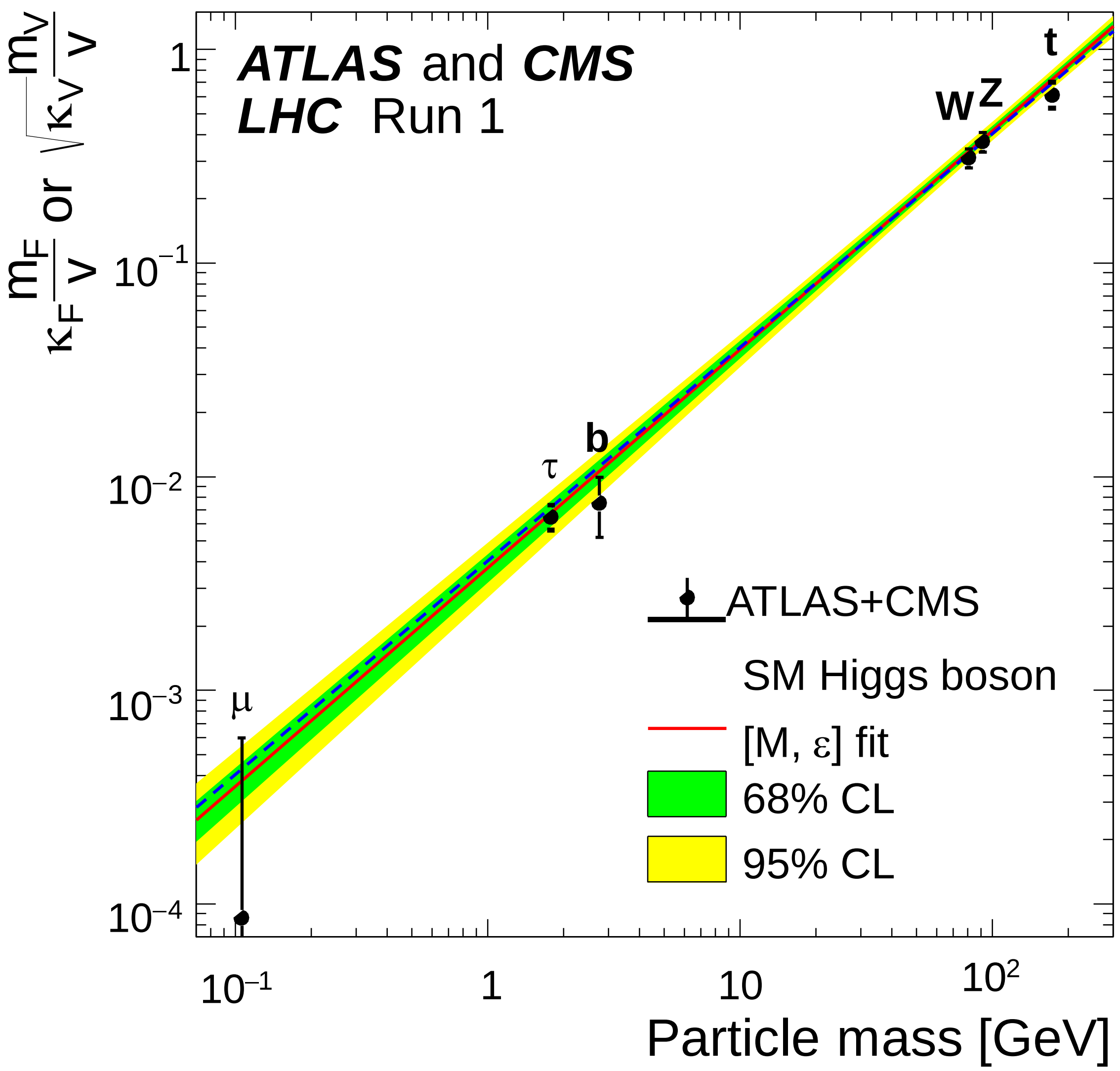
Rejection = 1/ mis-tag-efficiency

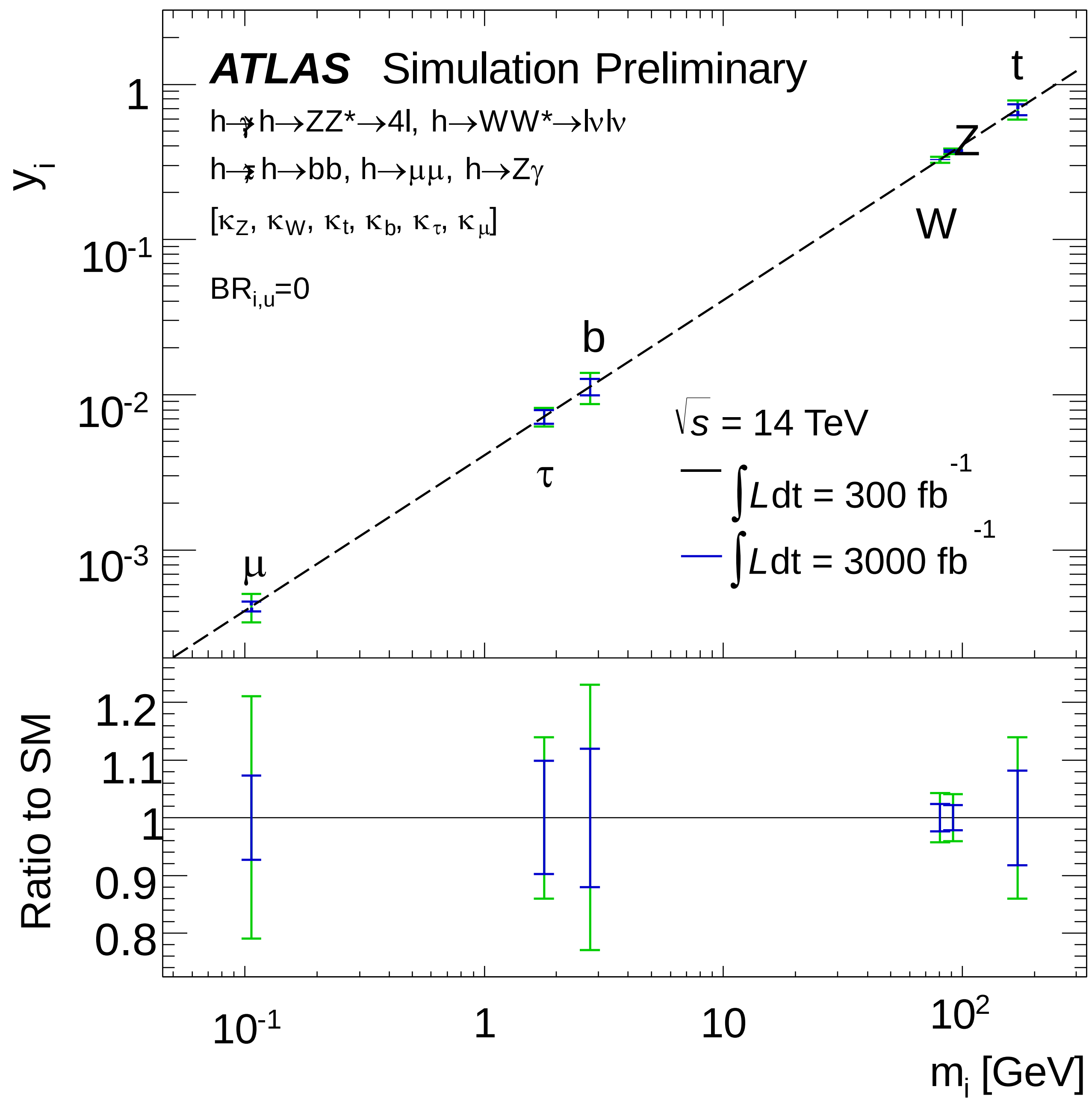


Higgs boson

JHEP 08 (2016) 045
ATL-PHYS-PUB-2014-016

- Example coupling plots from Run 1 and for HL-LHC
  - Typical precision improves from 10% to 4%. H→ μμ > 7σ





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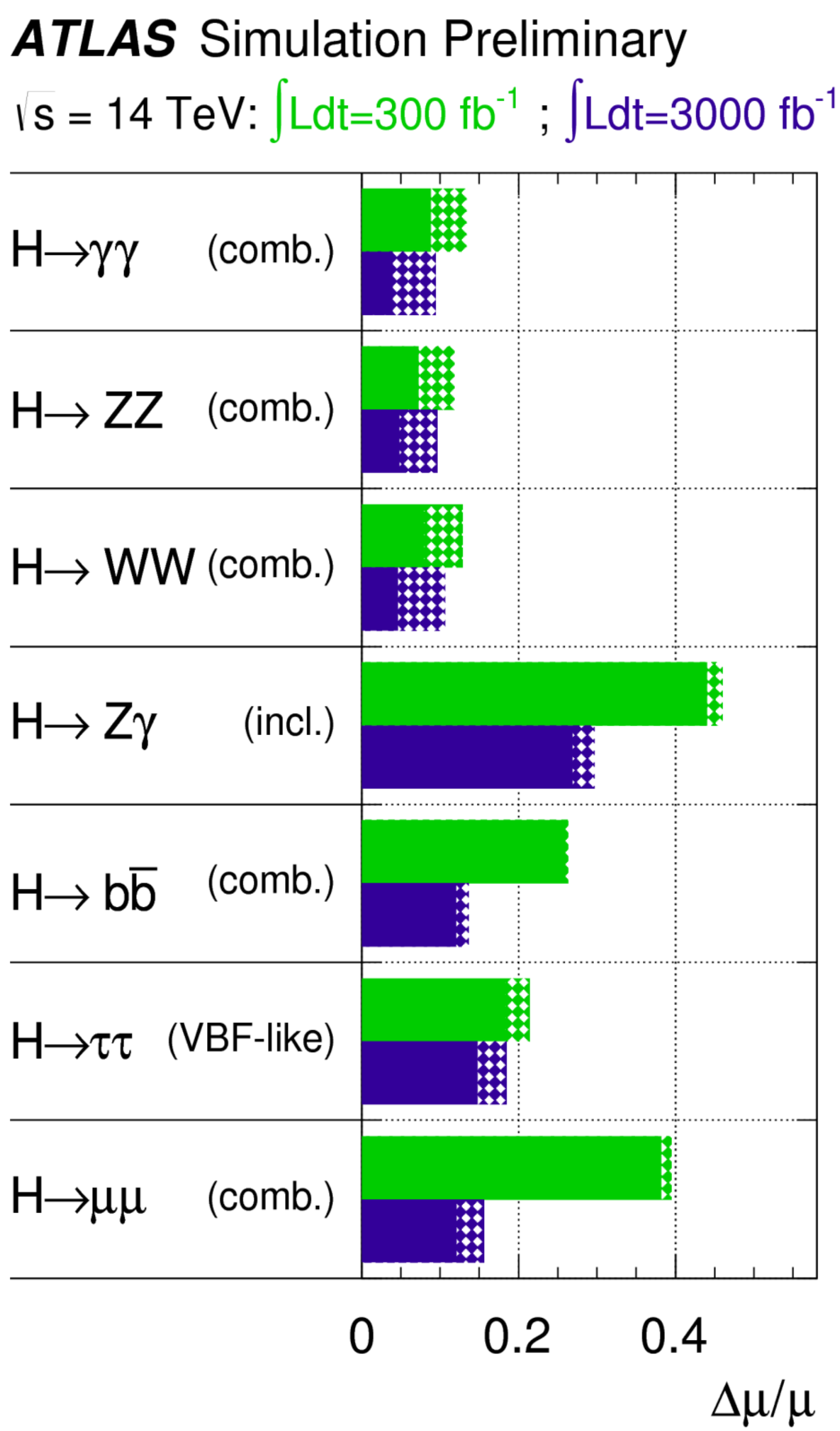
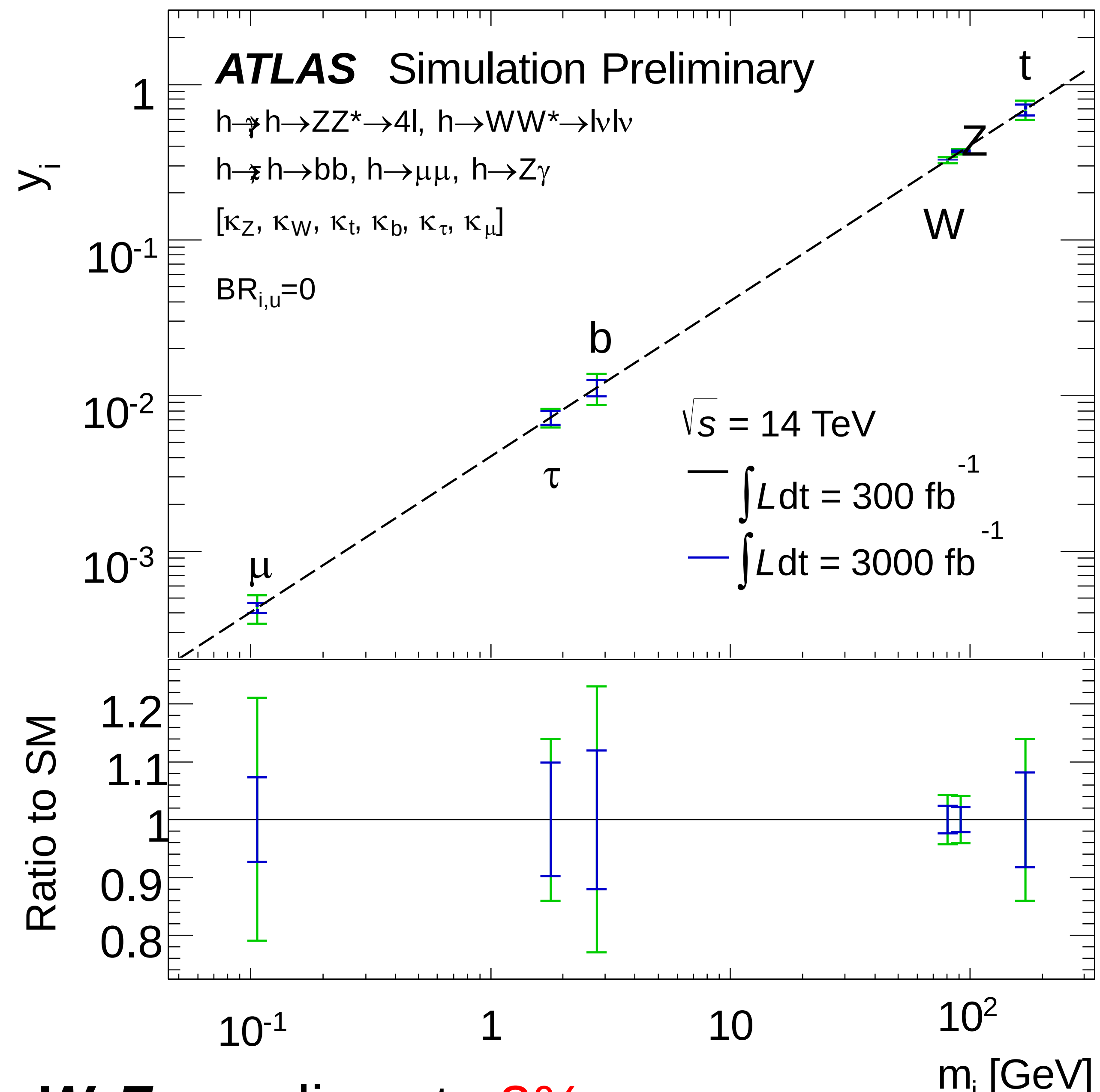
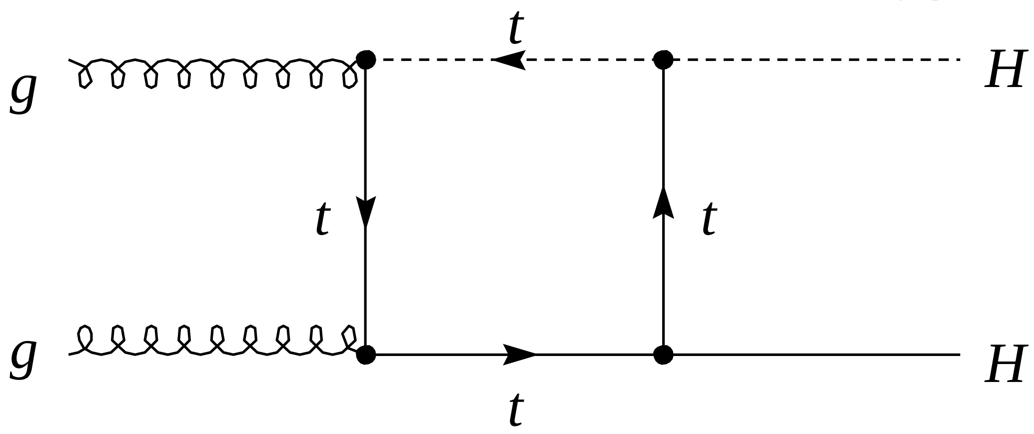




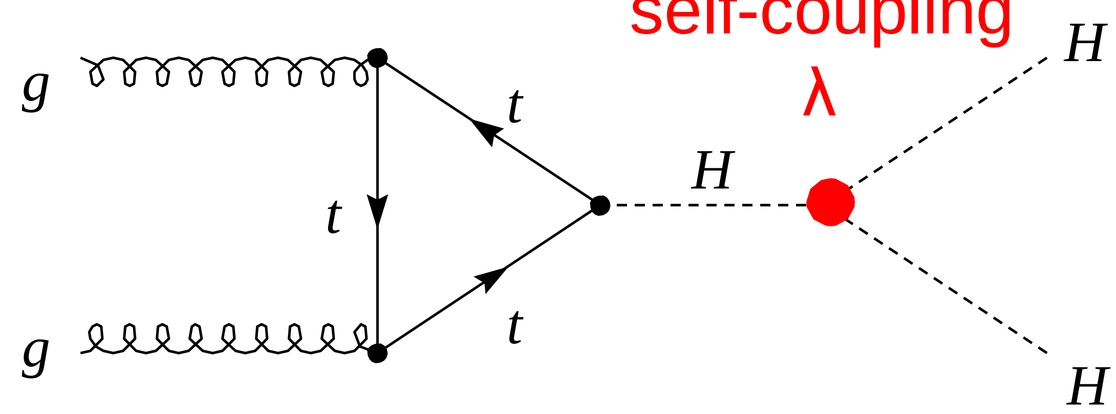
- ***W, Z*** couplings to 3%
- ***Muon*** coupling to 7%, ***t,b,τ*** couplings to 8-12%

Higgs boson pair production

- Higgs boson pair production includes destructive interference between two types of processes:



Higgs triple self-coupling λ



- ~factor 2 increase in cross section if $\lambda \rightarrow 0$

NNLO σ^{SM}=40.8 fb

- Will have to combine several decay modes and both experiments to have evidence

- More generally – explore electroweak symmetry breaking in Vector Boson Scattering

Channel	Events in 3/ab	Significance for HH (λ=1)
bbbb	40000	0.6 σ
bbWW	30000	(ttbar backgr)
bbττ	9000	0.6 σ
WWWW	6000	
γγbb	320	1.05 σ
γγγγ	1	

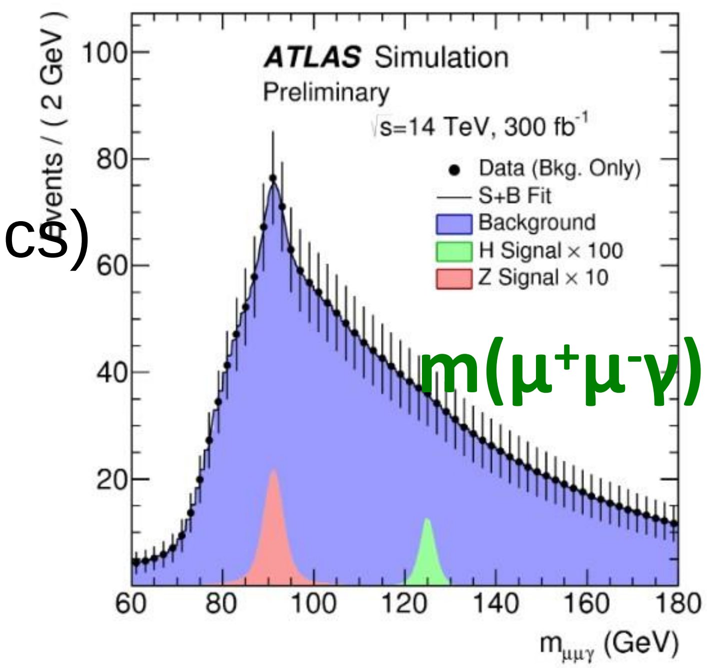
Higgs rare decays

- **$H \to J/\Psi\ (\to \mu^+\mu)\ \gamma$** (with $<\mu_{PU}>=140$, L = 3000 fb^{-1})
  - Higgs coupling to c-quark. Run-1 detector performances
  - MVA analysis $m_{\mu+\mu-\gamma}$ in [115, 135] GeV
  - 3 signal events and 1700 background (with no systema;cs)

BR ($H \to J/\Psi (\to\mu\mu)\gamma$): 44^{+19}_{-22} x 10^{-6} (95% C.L.)

SM: 2.9 ±0.2x10^{-6} (Run-1 Limit: 1.5 x 10^{-3})

(ATL-PHYS-PUB-2015-043)

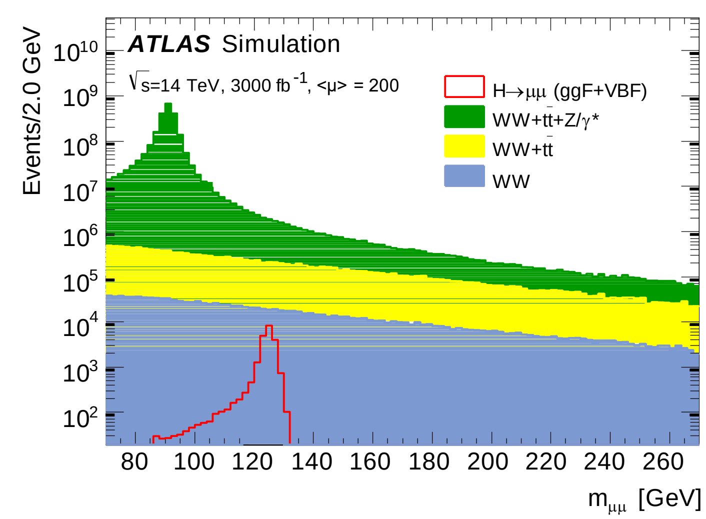


- **$H \to \mu^+ \mu^-$** (with $<\mu_{PU}>=200$, L = 300/3000 fb^{-1})
  - Low BR, high Z/γ* background, high mass resolution
  - Based on Run-1 analysis , $m_{\mu+\mu-}$in [110, 160] GeV]
  - Total background shape and normalization data-driven
  - ITK-Upgrade -> improve **mass resolur on by 25%** (w.r.t Run-2

Z_0: 2.3σ (300 fb^{-1}) 7.0σ (3000 fb^{-1})

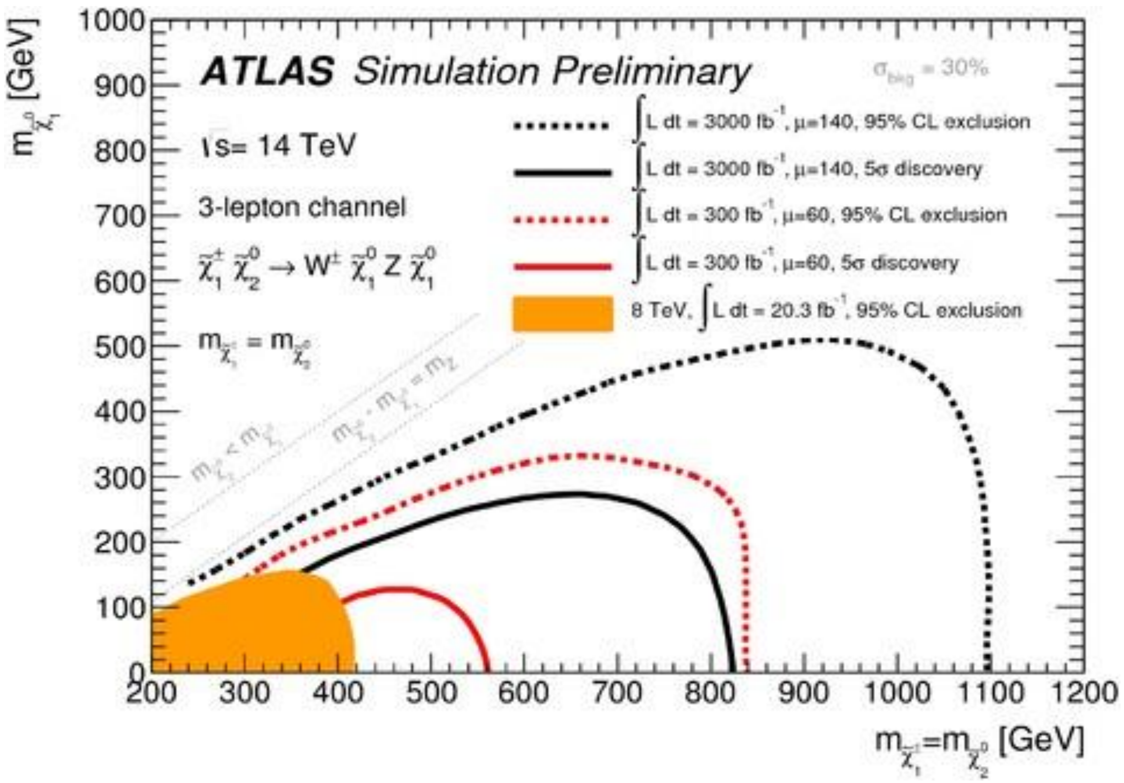
Δμ/μ: 46% (300 fb^{-1}) 21% (3000 fb^{-1})

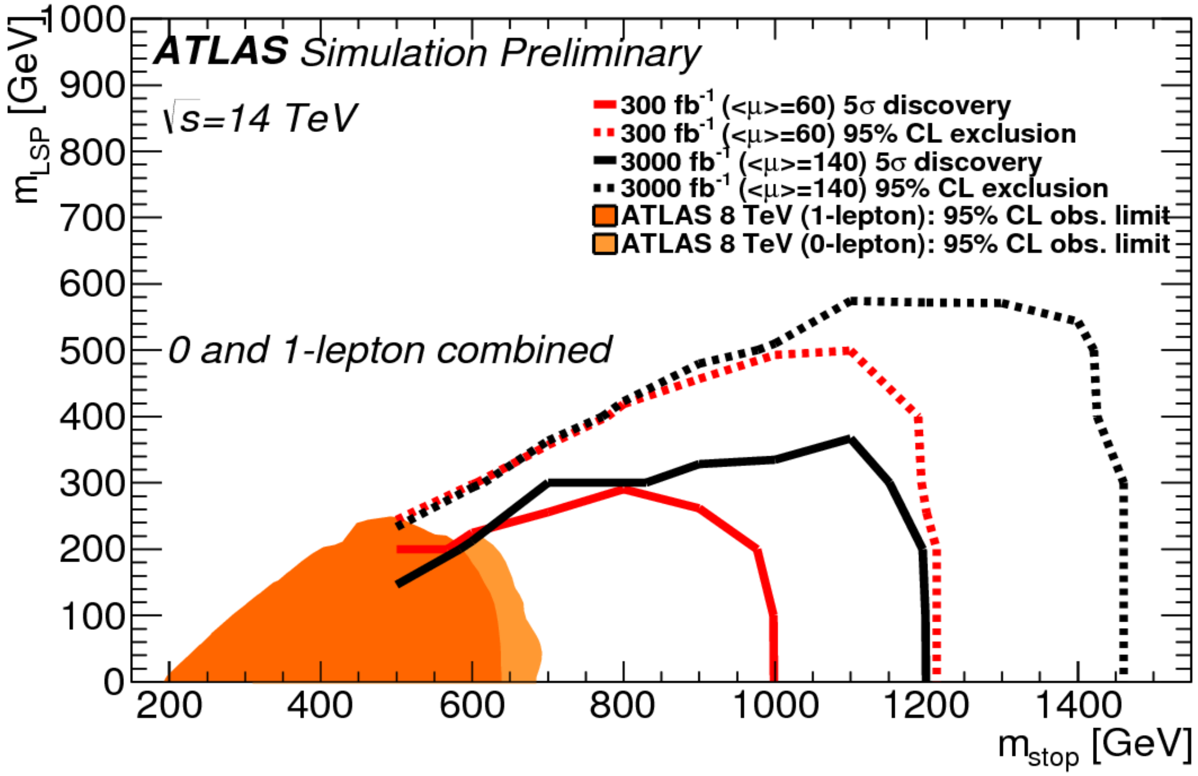
(ATL-TDR-025 LHCC-017-055)



Search reach (300/fb vs 3000/fb)

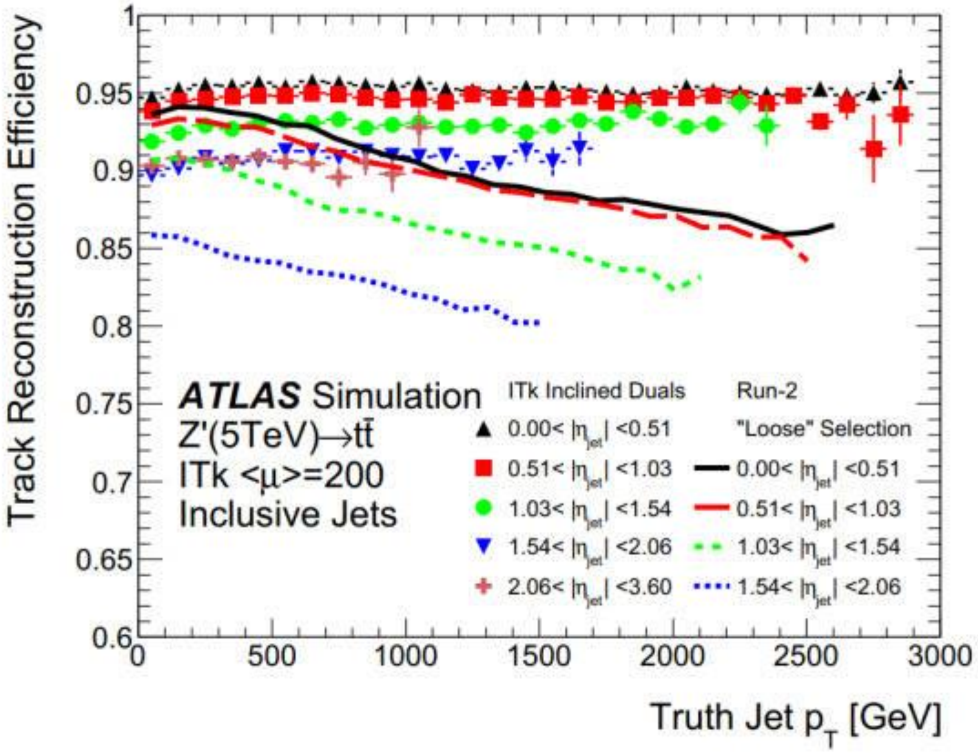
- Electroweak SUSY, extend from 500-600 GeV to 800-900 GeV
- Scalar top/bottom, few 100 GeV increase in reach



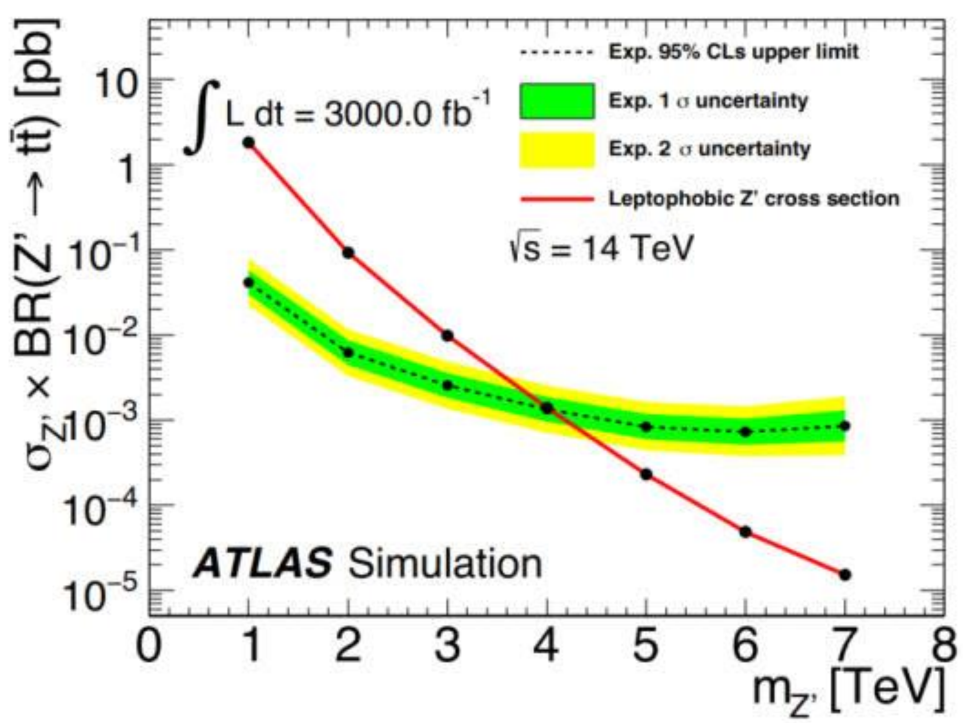


Expected sensitivity for Z'→ $t\bar{t}$

- Single lepton + jets channel ($t\bar{t} \to WbWb \to l\nu bqq'b$)
- **Stable tracking efficiency inside jets with increasing p_T**
  - Top quarks tend to produce b-jets with $p_{\mathrm{T}} > 600$GeV
  - **Robust against the high-density tracking environment**



- If no signals observed, expect to exclude this resonance for $m_{Z'} < 4$ TeV after HL-LHC (ATL-PHYS-PUB-2017-002)
  - Topcolour model of spin-1 Z' assuming $\Gamma = 1.2\%$
  - LO×1.3 to account for NLO effects
  - The most recent ATLAS search using 36.1 fb^{-1} of data taken at $\sqrt{s} = 13$ TeV excludes $m_{Z'} < 3.2$ TeV (Talk by Siyuan Sun)



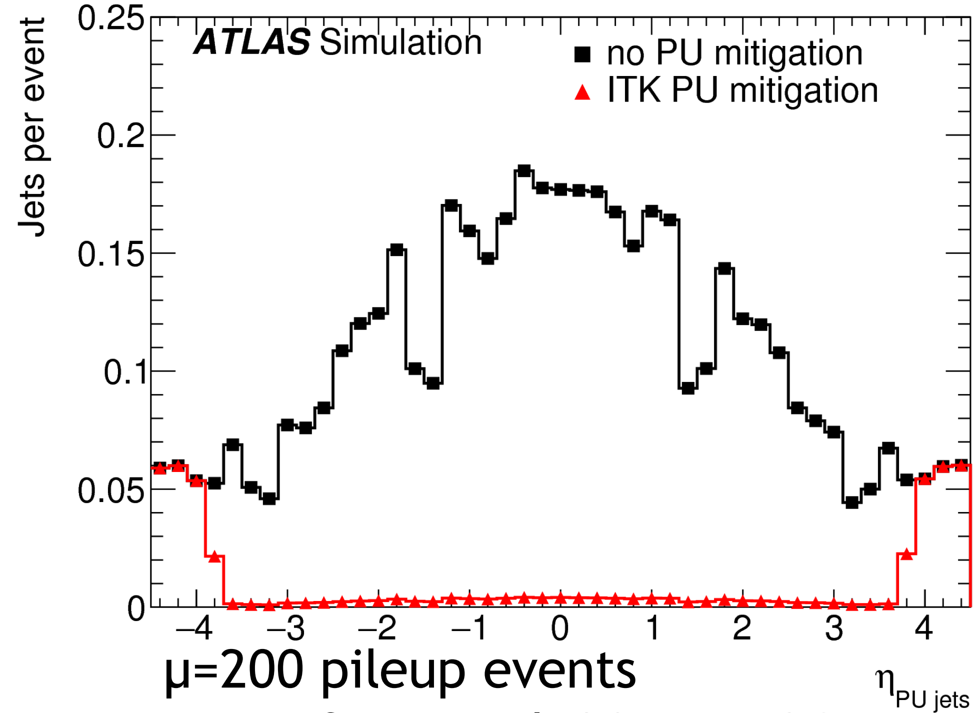
Summary

- Challenging to maintain or improve performances in very dense environment with pileup up to 200
- Significant upgrades planned for the ATLAS detector for HL-LHC
  - All-silicon ITk with extended coverage to improve the tracking performance
  - HGTD to mitigate pile-up effects
  - Trigger system upgrade to keep lower trigger threshold
- The performance of the physics objects reconstruction is expected to be better than the current detector.
- HL-LHC critical for high precision measurement of the Higgs boson parameters as well as searches for physics BSM.
- Technical design reports (TDR) are planned for each upgrade project (Muon and Strip trackers are already released. Others will follow soon.

Backup

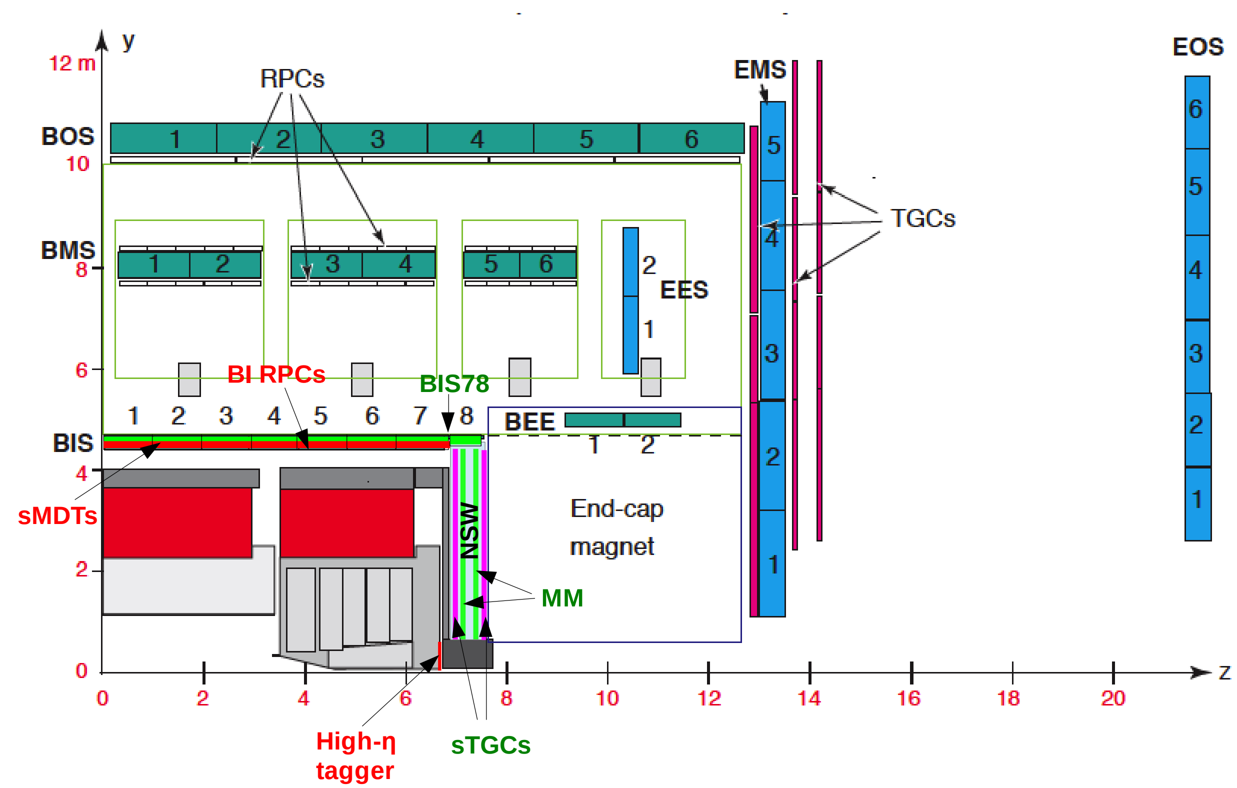
Phase-II for HL-LHC

- New all-silicon tracker ITk
  - Extending to $|\eta| < 4.0$
  - L1 track trigger
- Calorimeter electronics upgrade (full info at trigger level)



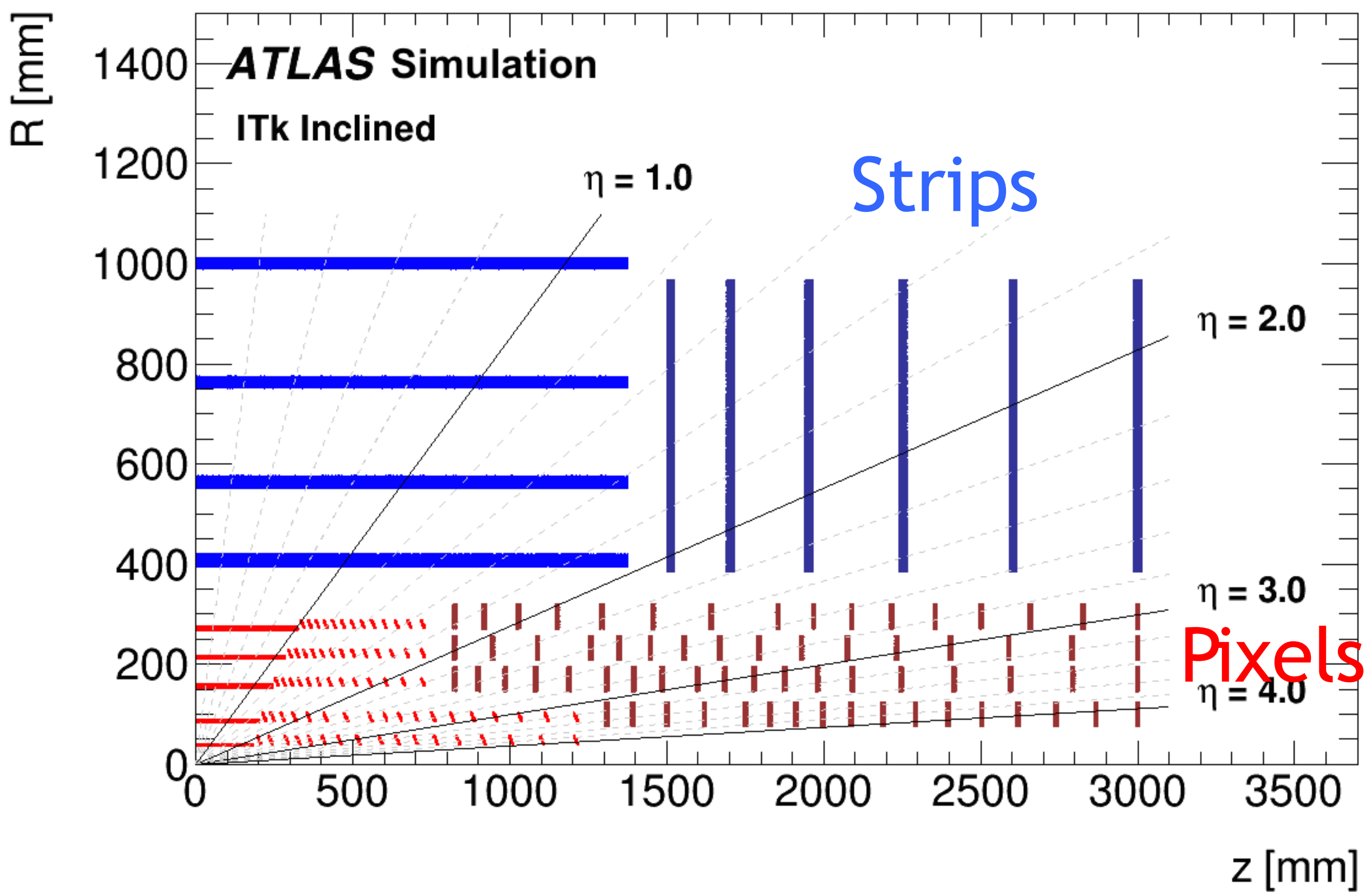
μ=200 pileup events
Rate of jets with 20<pT<40GeV

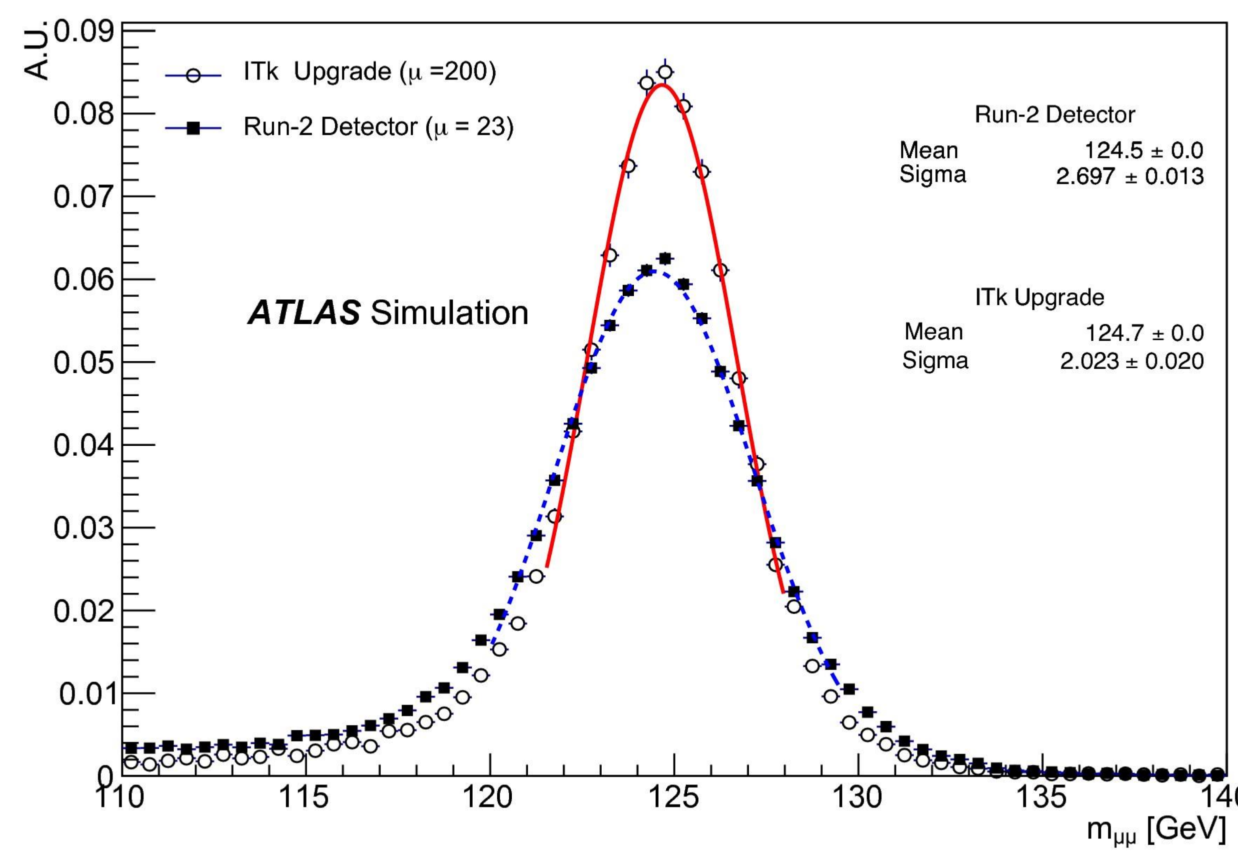
- Muon system upgrades (fill gaps in trigger coverage with new inner barrel chambers; new front-end electronics)
- Trigger-DAQ upgrades
- New projects:
  - High granularity timing detector for the forward region
  - Muon high-η tagger



HL-LHC studies in progress

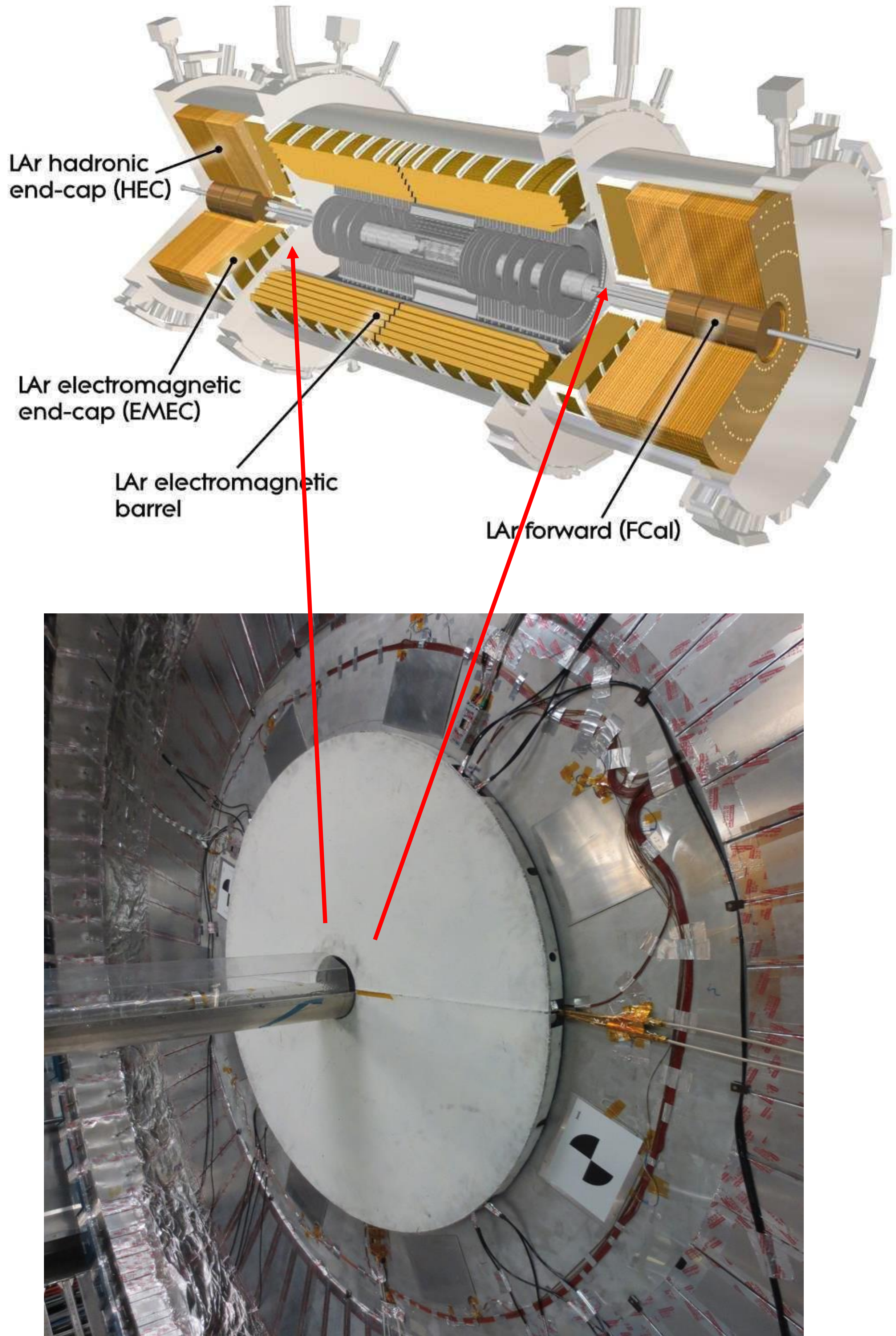
- Present efforts are focussing on TDRs for each Phase 2 upgrade
  - Demonstrate that the detector and trigger choices meet the required performance
  - ITk layout from the Strip TDR and improvement in Hà μμ mass





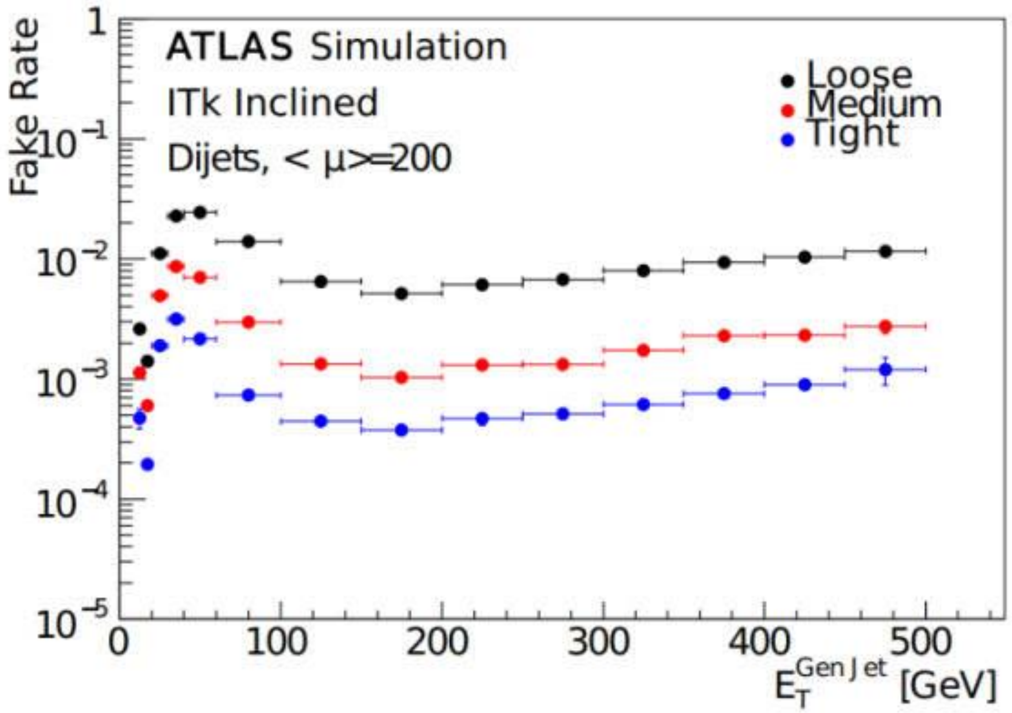
- More comprehensive physics prospects planned for Update of European Strategy for Particle Physics
- HGTD TDR planed for end of 2018

HGTD location

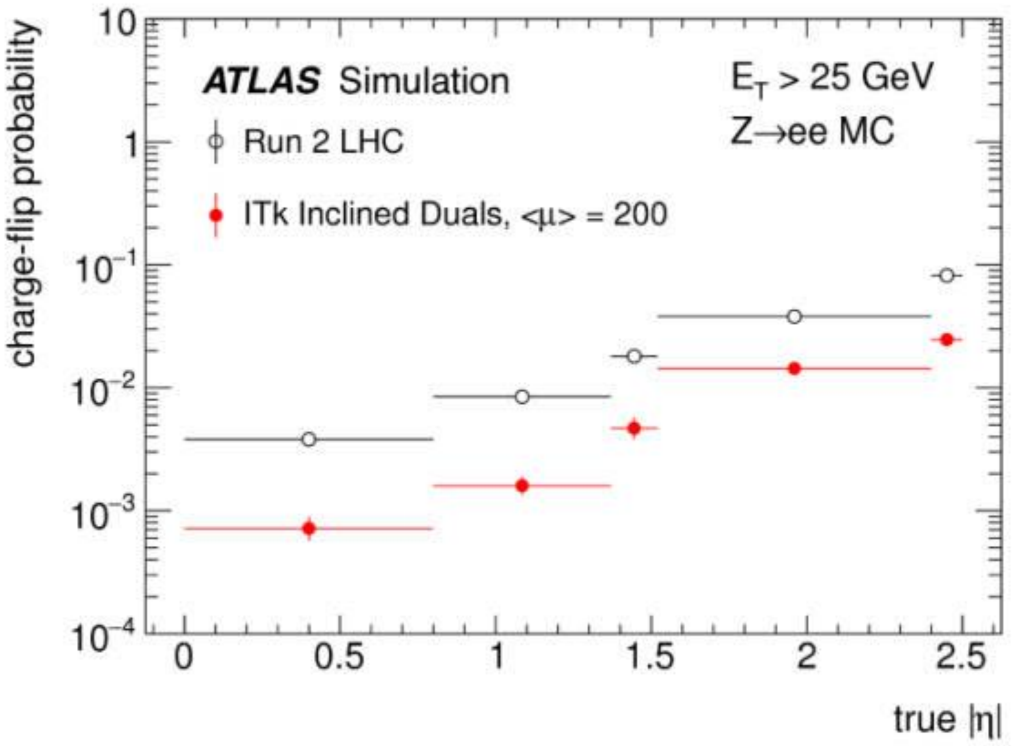


Performance of electron reconstruction

- **Similar performance with Run2 is expected**
  - Likelihood based electron identification, combing calorimeter and track variables
  - It improves about a factor of 2-5 in rejection of jets.
  - This would also be carried out for ITk.

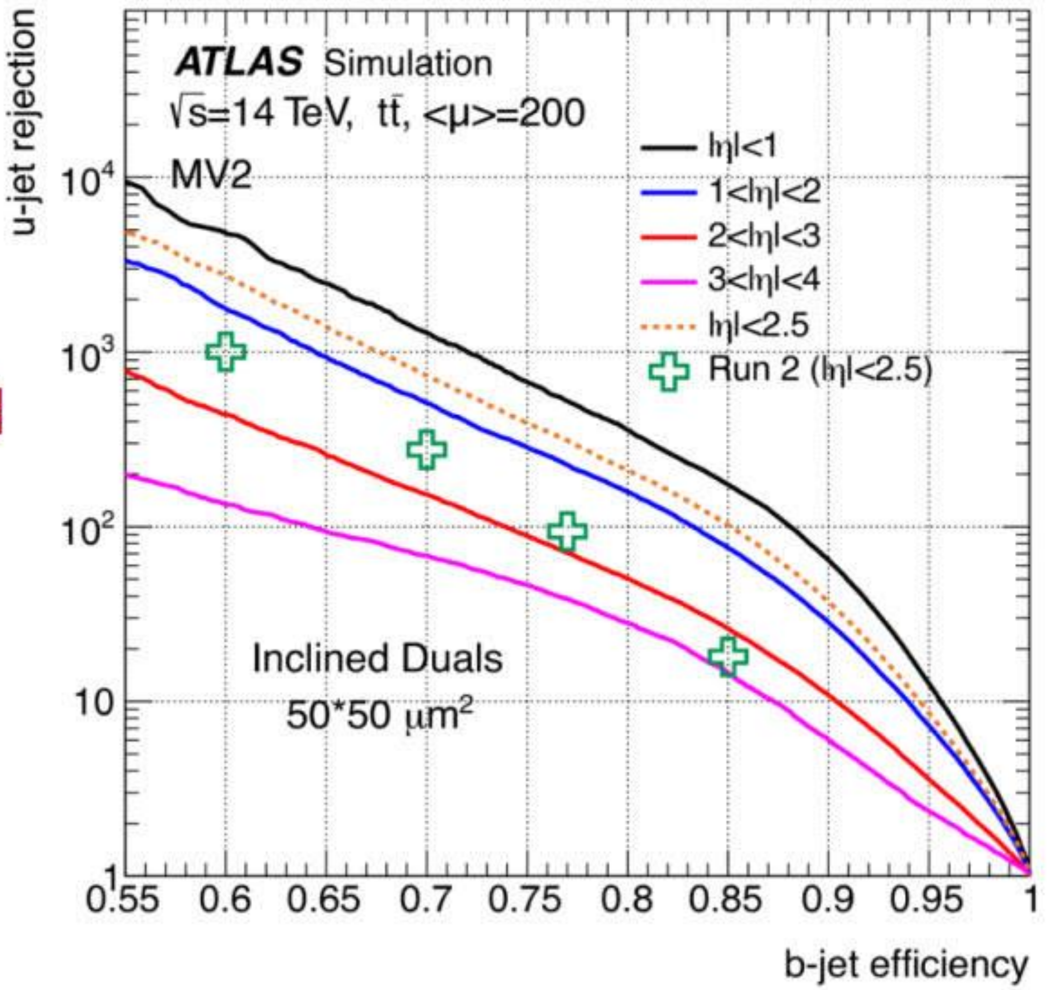


- **Charge mis-identification** is caused predominantly by Bremsstrahlung .
  - The EM cluster corresponding to the initial **matched** to the wrong-charge from the conversion leptons
  - The electron track may fail the tracking recovery for Bremsstrahlung, leading to a **poorly measured short track**.
  - ➢ **Reduced material of ITk significantly decreases the mis-identification probability.**



b-tagging performance

- **Multivariate techniques** based on
  - Impact parameters of associated tracks
  - Properties of reconstructed secondary vertex
- ***b*-tagging algorithms have been fully re-optimized for the new layout**
  - **Better rejection capability of ITk even at high pile-up levels**
  - **The extended coverage of ITk enables the *b*-tagging in the forward region.**



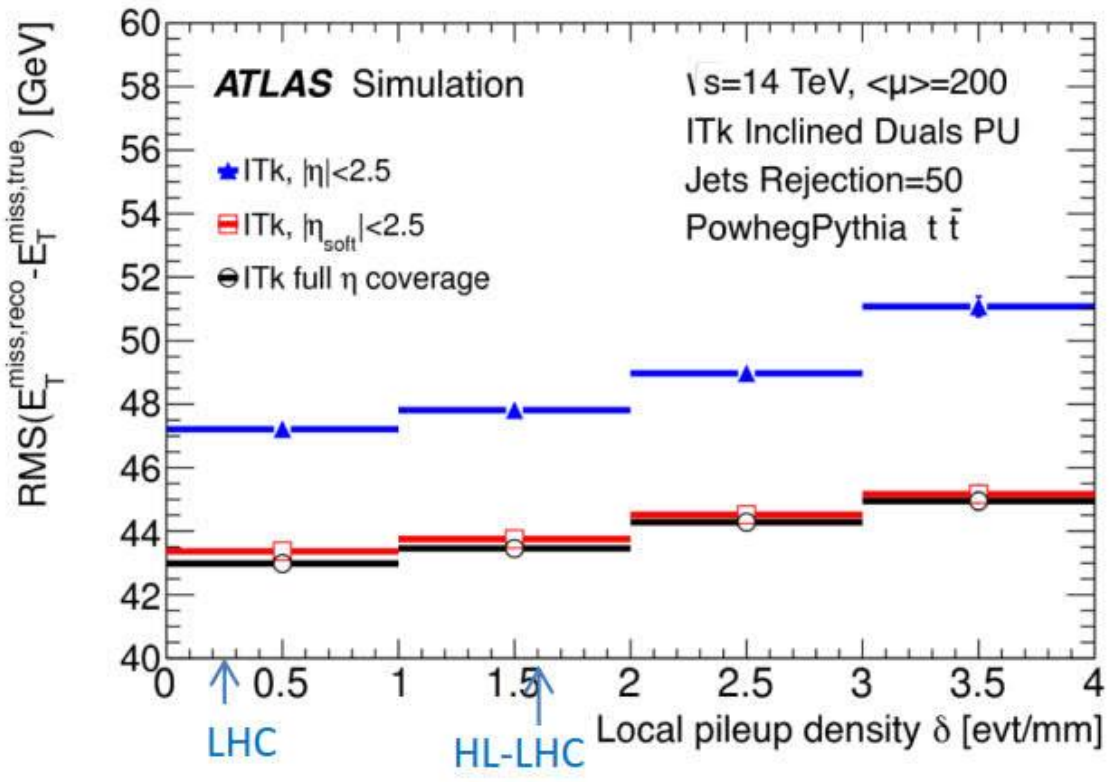
- *b*-tagging is sensitive to the contamination of pile-up tracks
  - It considers **tracks with large impact parameters**
  - **Essential to mitigate effects from pile-up**

Performance for Missing Transverse Momentum

- **An important variable in searches for exotic signatures.**
  - In SM, $E_{\mathrm{T}}^{\mathrm{miss}}$ arises from neutrinos.
  - There are also prospects for such particles in BSM theories.

- $E_{\mathrm{T}}^{\mathrm{miss}}$ is computed as the vector momentum sum of high p_{T} physics objects, plus the soft-term from low p_{T} particles associated to the HS vertex.

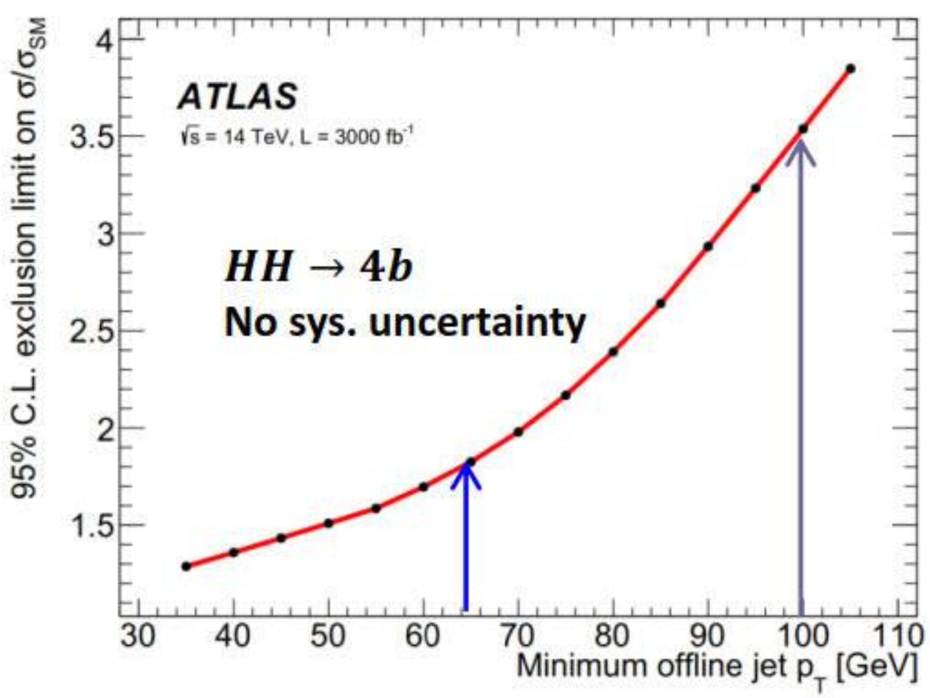
- **Better E_{T}^{miss} resolution** in the high pile-up conditions
  - ✓ Benefitting from the strong **pile-up jet rejection of ITk** in the forward region
  - ✓ The gain in the soft term using tracks in the forward region is small

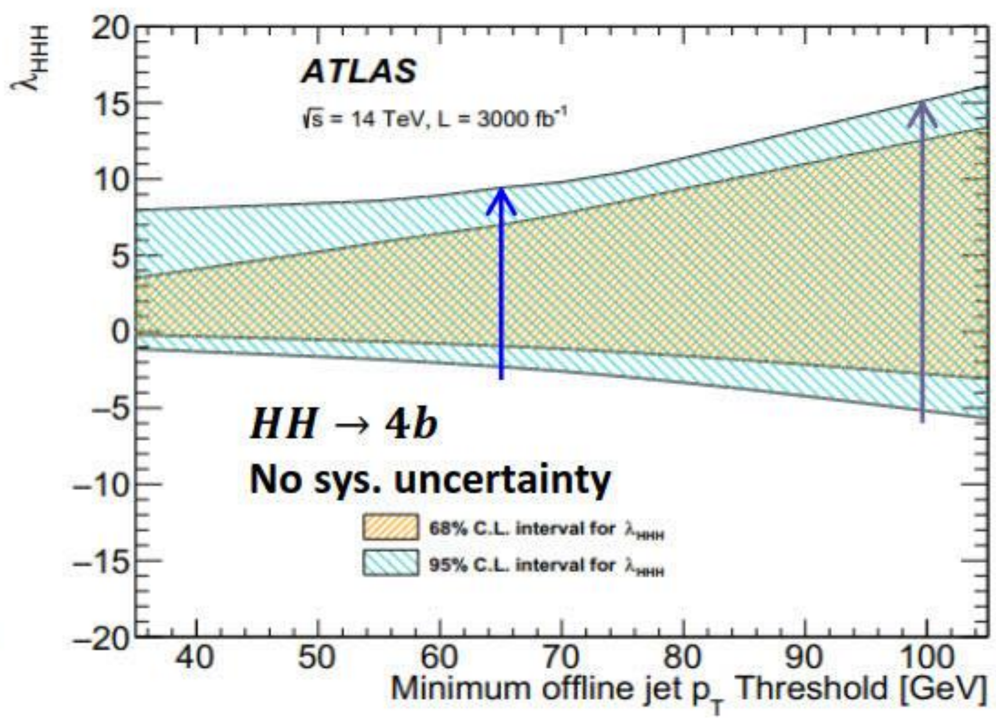


- HGTD timing information would improve E_{T}^{miss} performance with better pile-up rejection in the forward region

Expected sensitivity to H→*bb*

- **The effects of upgraded ATLAS detector are taken into account** by
  - applying energy smearing, object efficiencies and fake rates to truth level quantities
  - following parameterizations based on detector performance studies with full simulation and HL-LHC conditions
- $HH \rightarrow 4b$ High sensitivity to b-jet trigger threshold → Trigger system upgrade is critical
  - Substantial degradation with increased minimum jet p_T requirement
  - 100 GeV → 65 GeV (w/o → w/ upgrade) ~ $\times$ 2 sensitivity





- **More channels combined to get enough statistics**
  - $b\bar{b} + \gamma\gamma$
  - $b\bar{b} + \tau^+\tau^-$
  - ……